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# DESIGN REQUIREMENTS AND DEVELOPMENT OF AN AIRBORNE DESCENT PATH DEFINITION ALGORITHM FOR TIME NAVIGATION

**K. H. Izumi, J. L. Thompson, J. L. Groce, and R. W. Schwab**

**Boeing Commercial Airplane Company
Seattle, Washington**



**Contract NAS1-16300
May 1986**

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National Aeronautics and
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**Langley Research Center**
Hampton, Virginia 23665

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# 1.0 SUMMARY

This document describes the design requirements for an airborne version of the Local Flow Management/Profile Descent path-definition algorithm. These requirements specify the processing flow, functional and data architectures, and system input requirements, and recommend the addition of a broad path-revision functional capability. The document also summarizes algorithm design enhancements and the implementation status of the algorithm on an in-house PDP-11/70 computer, which is similar to the flight-selected Norden computer. Finally, the requirements for pilot-computer interfaces, lateral path processor, and guidance and steering function are described.

# 2.0 INTRODUCTION

This document is a description of the functional requirements and the current implementation status of the airborne Local Flow Management/Profile Descent (LFM/PD) path definition algorithm. The algorithm calculates either a 3D minimum-fuel arrival descent profile or a 4D minimum-fuel arrival descent profile when en route metering (ERM) is in effect. The profiles accommodate all air traffic control (ATC) clearance and procedural constraints. Local Flow Management/Profile Descent was the nomenclature given to the fuel-saving ATC descent procedures in effect when algorithm development was initiated. Although the application of profile descent procedures is currently limited to only a few runways and that local flow management time-based metering has been superseded by ERM, the algorithm is compatible with the latest Federal Aviation Administration (FAA) procedures.

This is a report of progress made under Task Requirement A-1, Local Flow Management Avionics, of NASA contract NAS1-16300, to (1) extend the capabilities of the fast-time path definition algorithm developed under Task Requirement A-103 of NAS1-14880, and (2) develop an airborne-compatible version of the algorithm for installation on the Norden computer. The Norden, an airborne equivalent of the PDP-11/70 computer, is part of the planned Transport System Research Vehicle (TSRV) B-737 experimental test bed. The airborne algorithm requirements and proposed implementation described in this document represent subsequent work toward an operational airborne capability.

Functional requirements for development of an airborne algorithm are detailed in Section 4.0. Section 5.0 describes the proposed computer model implementation on the Norden. Airborne system interface requirements are described in Section 6.0. A complete description of the functional logic, computer model structure, and testing of the previously developed fast-time LFM/PD algorithm is contained in reference 2.

## 2.1 BACKGROUND

Local Flow Management/Profile Descent procedures were established on November 15, 1976, by the Local Flow Traffic Management national order 7110.72. The order not only specified operational guidelines for complying with the goal "to enhance safety, conserve aviation fuel and reduce the impact of aircraft noise on the local communities," but established a metering program as well. The function of the latter is to monitor the arrival flow in relation to system capacity and, if required, to meter aircraft so as not to exceed this capacity. When metering is to be put into effect, actual landing times are assigned according to calculations of estimated arrival times and the application of a prioritization rule when simultaneous arrivals are predicted to occur. A landing time is translated into a crossing time at one of several published waypoints known as meter fixes, which may require imposition of ATC delay for the aircraft to make good the time.

Profile descent procedures were published at Denver, Atlanta, St. Louis, Los Angeles, Miami, and San Francisco. Prototype time-based metering programs were developed at Denver and Ft. Worth centers. The metering function has subsequently been integrated into the NAS stage A software and is now available at all centers as ERM. Beyond these current metering programs, the FAA has several advanced flow management concepts under study or development. These include terminal metering, automated en route ATC, and terminal area tactical execution. These concepts form the basic building blocks for evolution of the ATC system flow management function from today's time-based metering to the 1990 to 2000 Air Traffic Management system.

## 2.2 NASA ADVANCED TRANSPORT OPERATING SYSTEMS (ATOPS) LFM RESEARCH

The LFM avionics research program was established to define the airborne navigation and guidance capabilities needed for efficient operation in the ATC flow management system under development. The NASA Local Flow Management avionics research plan is shown in Figure 1. This plan was developed under NAS1-14880, TR AB-11. Subtasks 1 and 2 under NAS1-14880 have been completed and a contractor report was published, which delineated the major areas to be addressed in the LFM research plan (ref. 1). Subtasks 3 through 9 identified in Figure 1 are being pursued as part of the long-range research effort.

The design of the basic, generalized algorithm to provide path definition computations was completed in July 1979. The development of additional capabilities (including holding and path stretching considerations) and refinement of the algorithm based on analysis, simulation and flight test results were completed in July 1980 (ref. 2). The airborne algorithm design requirements were specified in December 1981 (ref. 3). These requirements are summarized in Sections 4.0 and 6.0. The work to install the basic algorithm on an in-house PDP-11/70 was begun in August 1981. The status of the airborne algorithm activity is summarized in Section 5.0.

## 2.3 AIRBORNE ALGORITHM DEVELOPMENT TASK

The algorithm design requirements, as described in Section 4.0, make a demanding core size requirement on the flight computer. The current CYBER FORTRAN (fast-time) version requires 151,000 octal words. Features described in Section 4.0 have been incorporated into the basic algorithm, except for some path revision capabilities (described in subsection 4.5) that are to be used in response to changes in the planned descent due to weather or traffic. Implementation of the algorithm on the PDP-11/70 requires reduction to a maximum work space of 28,000 octal words by overlay management and other techniques. This implementation is described in subsection 5.2. Recommended additional capabilities to support path revisions are described in subsection 5.3.

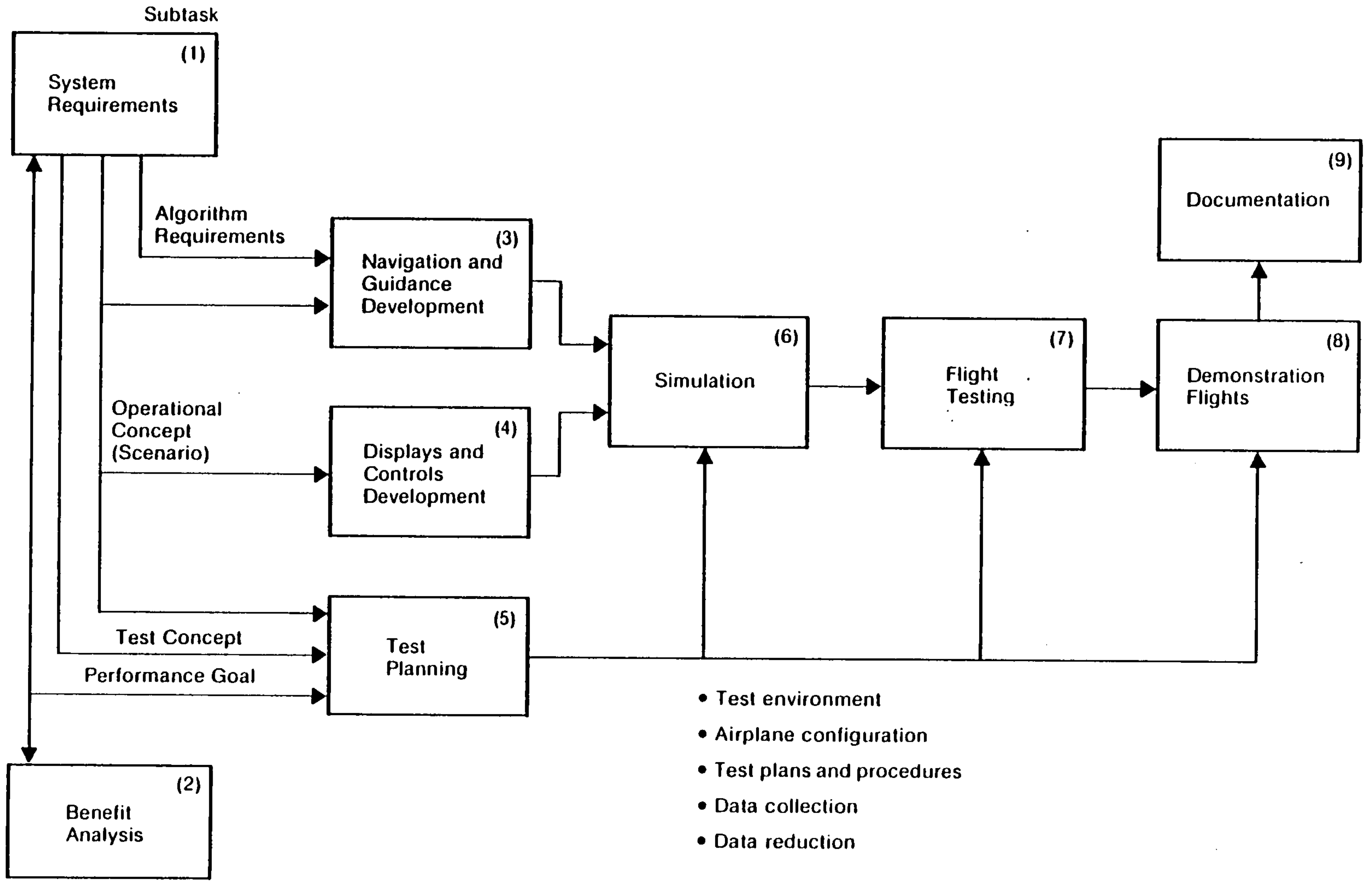


*Figure 1. Local Flow Management Avionics Research Plan*

# 3.0 SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| $\phi$ | bank angle |
| $\Delta\psi$ | course change |
| ADS | air data system |
| AFDI | automatic flight director indicator |
| ARTCC | air route traffic control center |
| ATC | air traffic control |
| ATOPS | Advanced Transport Operating Systems |
| CAS | calibrated airspeed |
| $C_D$ | drag coefficient |
| CDU | control and display unit |
| EADI | electronic attitude/director indicator |
| EHSI | electronic horizontal situation indicator |
| EPR | engine pressure ratio |
| ERM | en route metering |
| ETA | estimated time of arrival |
| $F_n/\delta$ | corrected net thrust |
| FAA | Federal Aviation Administration |
| FMC | flight management computer |
| FMS | flight management system |
| g | acceleration due to gravity |
| GMT | Greenwich Mean Time |
| IRS | inertial reference system |
| ISA | International Standard Atmosphere |

| | |
|---|---|
| kcas | knots calibrated airspeed |
| LFM/PD | Local Flow Management/Profile Descent |
| MFT | meter fix time |
| MSL | Mean Sea Level |
| NAS | national airspace system |
| NASA | National Aeronautics and Space Administration |
| nmi | nautical miles |
| $N_1$ | airplane turbine rpm |
| rpm | revolutions per minute |
| s | elapsed distance |
| STAR | standard arrival route |
| $\Delta t$ | elapsed time |
| $\Delta T$ | change in absolute temperature |
| TAT | total air temperature |
| TNAV | time navigation |
| TOD | top-of-descent |
| TSFC | thrust-specific fuel consumption |
| TSRV | Transport System Research Vehicle |
| V | ground speed |
| $V_{ef}$ | entry fix airspeed |
| $V_o$ | initial airspeed |
| 3D | three-dimensional |
| 4D | four-dimensional |

# 4.0 AIRBORNE ALGORITHM DESIGN REQUIREMENTS

This section describes the airborne Local Flow Management/Profile Descent (LFM/PD) algorithm design requirements. The requirements define the needed functional characteristics in an operational context and the interaction among the algorithm functional elements, pilot inputs, and sources of data. Functional and data architectures are also provided. In order to increase algorithm flexibility, the capability to make revisions to the flight plan (including during descent) is recommended for addition to the basic functions of the fast-time version described in Reference 2.

## 4.1 ALGORITHM PROCESSING FLOW

The flow of the various algorithm processes is depicted in Figure 2. This subsection describes the sequence of the algorithm's functional elements from the moment of algorithm initiation to the display of summary data. Subsection 4.4 describes the sequence of pilot inputs, which include activation of the algorithm, review of summary path and performance data, and subsequent action (communication to the flight management software to engage the path or accept revised inputs).

A description of the airborne descent algorithm processes follows. It is assumed that the pilot has requested a profile descent calculation on the control and display unit (CDU).

### 4.1.1 PRESENT POSITION CONDITIONS

When the profile descent algorithm is activated, parameter values defining the current airplane state are immediately determined by the airplane subsystems:

(1) airspeed

(2) pressure altitude

(3) lateral position (latitude, longitude)

(4) gross weight

(5) time

These data form the basis for calculating airplane state at the entry fix.

### 4.1.2 ENTRY FIX CONDITIONS

The entry fix is the point at which the descent-path initial conditions are defined. It provides a waypoint reference where the projected airplane state must be a boundary condition constraint on the profile computation solution. The fix is placed at five minutes ahead of present position, allowing sufficient time for all requisite inputs and algorithm computations to take place, and for computed path engagement (coupling to the autothrottle and autopilot). Entry fix calculations should yield:

(1) lateral position

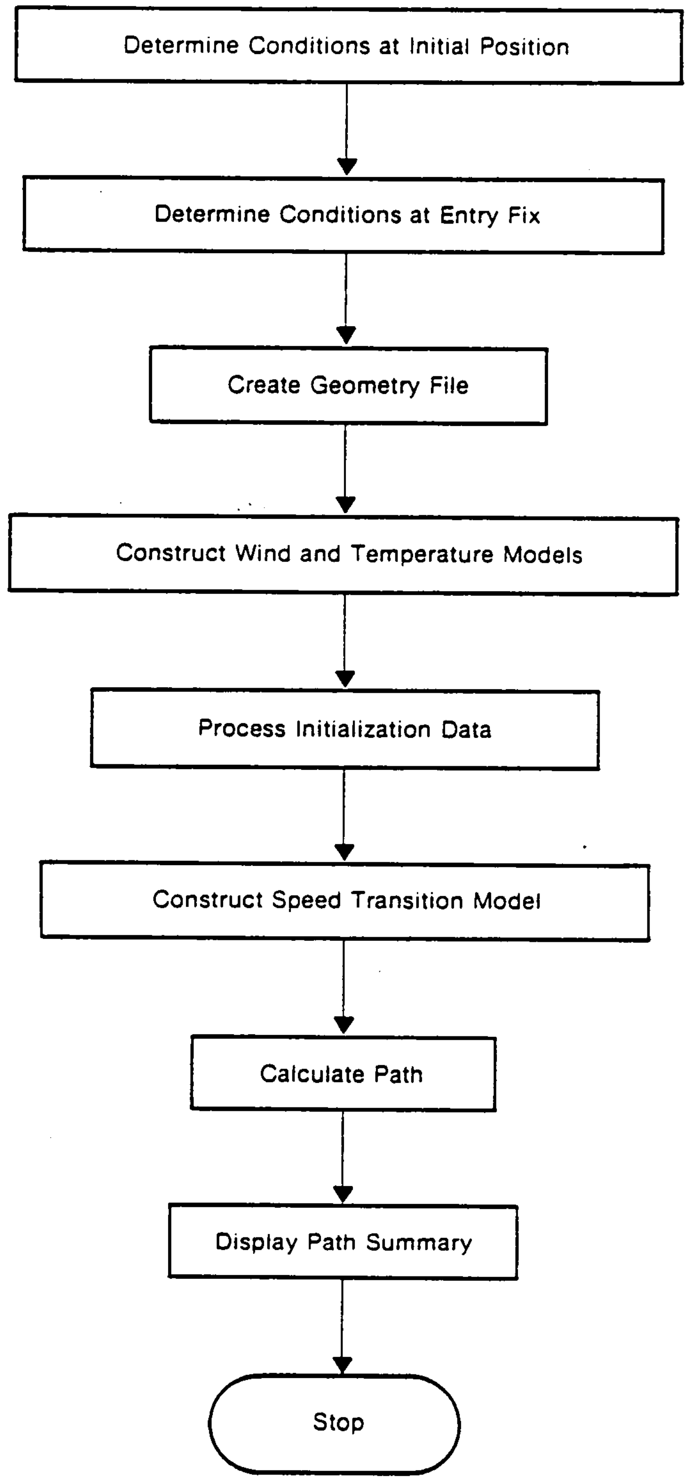


*Figure 2. Descent Algorithm Processing Flow*

(2) gross weight

(3) time

Entry fix speed and altitude are assumed to be the same as those at present position (paragraph 4.1.1).

### 4.1.3 GEOMETRY FILE

The destination airport and arrival procedure (meter fix and runway specifications) are supplied as part of the preflight inputs. The arrival procedure may be published as a profile descent or a standard arrival route (STAR). Algorithm utility will be extended by the additional capability to change the airport and path through the CDU prior to algorithm activation. The nominal arrival path procedure from the navigation data base will have been loaded into the path buffer. Any commanded geometry changes will automatically load the appropriate data into the buffer.

### 4.1.4 WIND AND TEMPERATURE MODEL PROCESSING

Currently, the algorithm updates wind and temperature forecasts, which can be obtained as much as 18 hours prior to departure. The forecast data can be loaded into an input file during preflight and later changed when the algorithm on activation updates the forecast with cruise wind and temperature measurements. A correction function is assumed which linearly decreases from the measured value at cruise altitude to the forecast value at aimpoint altitude. Thus, the forecast winds and temperatures are adjusted proportionally with altitude. The option to input (via CDU) revised forecasts can be exercised. A linear wind model assuming measured wind at cruise and zero ground wind, and a temperature model assuming ISA $\pm$ $\Delta$ T (where $\Delta T$ is the temperature variation at cruise) are the default models when no forecast data are provided.

### 4.1.5 INITIALIZATION DATA PROCESSING

At this point, the algorithm requires the various pilot-supplied initialization inputs that specify the descent conditions. Status flags for metering, holding, and icing are processed, along with the appropriate data that define each state. The current geometry is also processed, including any revisions made prior to algorithm activation.

### 4.1.6 SPEED TRANSITION MODEL CONSTRUCTION

The model that defines the Mach-to-CAS transition altitude (as a function of airspeed) is constructed at this stage of the processing flow. An important design consideration was to make maximum use of the available time envelope, consistent with Mach/CAS procedures and gross weight, by the model's defining a constant CAS descent at minimum speed and the fastest Mach/CAS descent at maximum speed. An empirical linear relationship (altitude versus true airspeed) assumed between the two limits, as depicted in Figure 3, closely approximated the Mach/CAS families of descent speed schedules suggested in the B737 flight operations manual.

### 4.1.7 PATH CALCULATION

The descent path parameters, which conform to all ATC, airplane performance, and weather constraints, are calculated. The computed descent path is composed of two sections: the high profile, and runway profile. The former is defined as that portion from cruise altitude down to the terminal area, while the latter is the terminal area descent path. More importantly, the runway profile includes the approach path from the aimpoint outbound to the last waypoint where ATC speed constraints are published. The aimpoint is the target fix where the algorithm requires altitude and speed constraints. In contrast to the procedural nature of the runway profile, the high profile allows timed descents over a wide range of speed schedules in order to accommodate a time assignment at the meter fix. Data stored in the performance (airframe and engine) data bases are used to determine the path. The runway and high profiles for a typical descent at Denver Stapleton International Airport are depicted in Figure 4.

### 4.1.8 PATH SUMMARY DISPLAY

The algorithm will display a summary of the path data for pilot preview. Section 6 discusses the display in the context of the interface required with the CDU.

## 4.2 FUNCTIONAL ARCHITECTURE

The algorithm functional components include the following:

(1) navigation data input

(2) atmosphere modeling

3) profile and path initialization

(4) icing determination

(5) speed transition model construction

(6) runway profile path construction

(7) high profile path construction

(8) display generation

The elements of each component are defined in Figure 5.

## 4.3 DATA ARCHITECTURE

All the data tables and airplane constants used in the fast-time descent algorithm are also required for the airborne version data base. The data required for the descent calculations are categorized in Figures 6, 7, and 8 according to navigation, engine, and airplane characteristics.

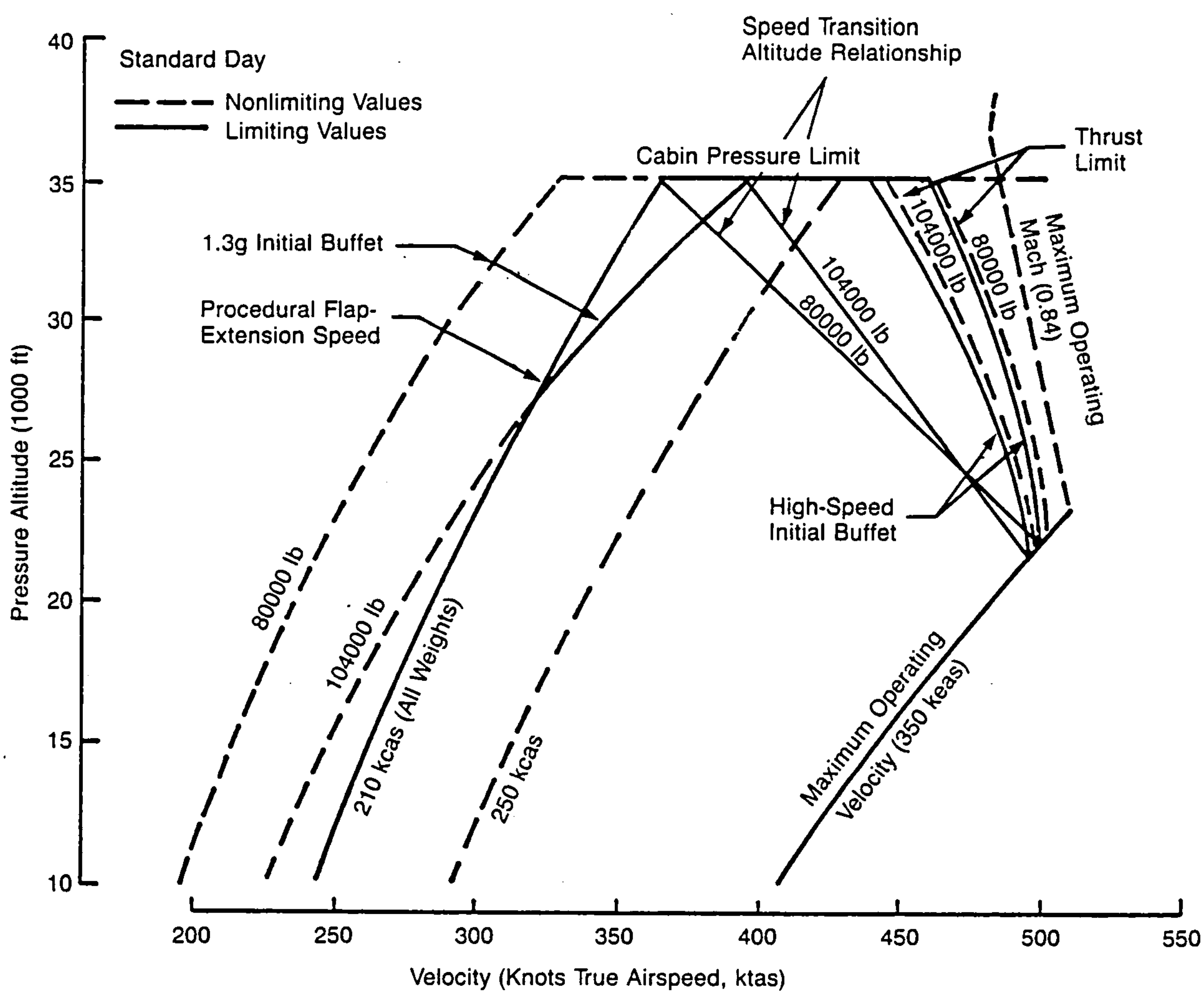


*Figure 3. Speed Transition Model Construction*

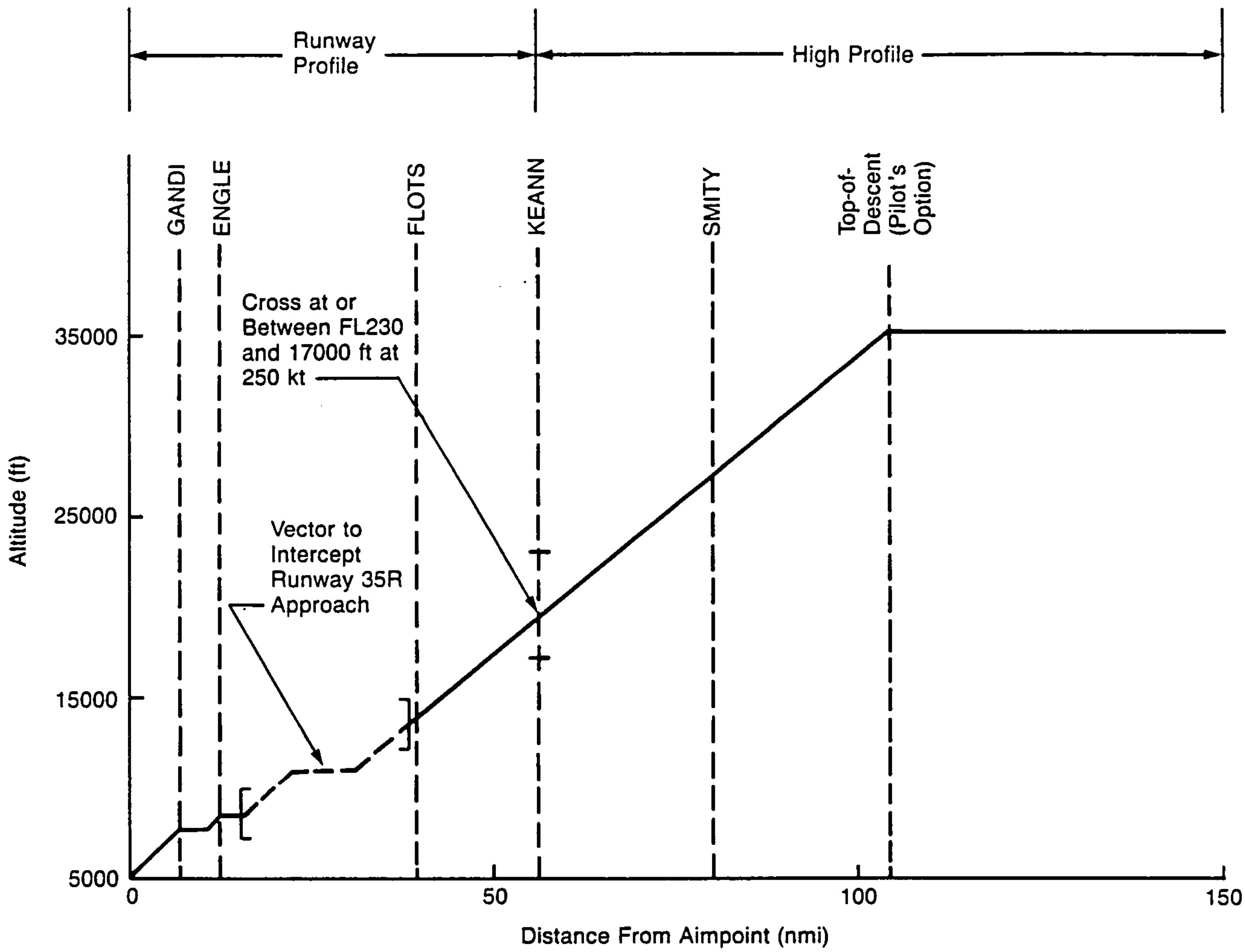


*Figure 4. Runway and High Profiles for a Typical Profile Descent (KEANN 35R, Denver Stapleton International Airport)*

**DESCENT PATH PREDICTION ALGORITHM**

- Navigation Data Input
  - Airport Selection
    - Path Selection
      - Geometry and ATC Constraints
- **Atmosphere Model Construction**
  - Vertical Wind Profile
  - Vertical Temperature Profile
- **Profile and Path Array Initialization**
  - Gross Weight Initialization
  - Geometry Revision
  - Altitude Assignments
  - Speed Restrictions
  - Entry Fix and Aimpoint Speeds
  - Airport Elevation
- **Icing Requirements Definition**
- **Speed Transition Model Construction**
- **Runway Profile Path Construction**
- **High Profile Path Construction**
  - Metering-Fix Time Assignment
  - Nonmetered Fuel-Efficient Path Definition
  - Descent Path Definition to Make Good MFT
    - Delay Profile
      - Holding
      - Path Stretching
    - No-Delay Profile
- **Display Generation**

*Figure 5. Algorithm Functional Structure*

NAVIGATION DATA

- **Airport 1**
  - Airport Elevation
  - Magnetic Variation
  - Profile Descent (STAR) (1,1)
    - Waypoint List
      - Aimpoint I.D.
      - Entry Fix I.D.
      - Standard Holding Fix I.D.
        - Holding Speeds
        - Inbound Leg Holding Magnetic Course
      - Standard Meter-Fix I.D.
    - Segment Magnetic Courses
    - Segment Distances
    - Waypoint Altitude Restrictions
    - Runway Profile Speed Constraints
  - Profile Descent (STAR) (1,2)
  - ⋮
  - Profile Descent (STAR) (1,m)
  - ⋮
- **Airport 2**
- ⋮
- **Airport n**
- ⋮

*Figure 6. Navigation Data Base Architecture*

**ENGINE DATA**

- **Fuel Flow Tables**
  - Idle Fuel Flow vs Mach, Altitude
  - Non-Idle TSFC vs Normalized Thrust, Mach, Altitude
- **EPR Tables**
  - EPR vs Corrected $N_1$, Mach, Altitude
  - Max Cruise EPR vs TAT
  - Max Climb EPR vs TAT
- **Thrust Tables**
  - Idle Thrust vs Mach, Altitude
  - Installed Net Thrust vs EPR, Mach
    - Net Thrust Correction vs Mach, Altitude

*Figure 7. Engine Data Base Architecture*

**AIRFRAME DATA**

- **Gross Weights**
  - Minimum Zero-Fuel Weight
  - Maximum Operating Weight
- **Speed Limits**
  - Slow Speed
    - Flap Extension
    - Slow Speed Mach Buffet vs Altitude, Weight
  - Fast Speed
    - Maximum Operating Mach
    - Maximum Operating Equivalent Airspeed
    - Thrust-Limited True Airspeed vs Weight, Altitude, Temperature
    - High-Speed Mach Buffet vs Altitude, Weight
- **Wing Area**
- **Number of Engines**
- **Service Ceiling Altitude**
- **Drag Polars**
- **Maximum $C_D$ vs Equivalent Airspeed**

*Figure 8. Airframe Data Base Architecture*

## 4.4 SYSTEM INPUT SPECIFICATIONS

Figure 9 illustrates the proposed sequence of pilot inputs and actions. Table 1 is a detailed summary of the inputs required by the algorithm to fulfill its path calculation function. The subsystem interfaces that are required with the path definition functions include:

(1) inertial reference system (IRS)

(2) air data system (ADS)

(3) internal clock

(4) on-line data bases

(5) fuel totalizer

(6) pilot inputs

Pilot entries on the CDU are assumed to be made through dedicated function keys or by menu selections. The following text elaborates on each entry type.

### 4.4.1 PREFLIGHT INPUTS

The FAA supplies twice-daily wind and temperature forecast data for 62 U.S. weather stations. The appropriate data for all destination airports are loaded into an input file. In addition, for the purposes of the descent calculations, the pilot should provide, through CDU inputs, the following data:

(1) city pair

(2) planned arrival route (including meter fix and runway)

(3) forecast winds and temperatures at the destination airport

(4) current Greenwich Mean Time (GMT)

(5) preliminary meter fix time (if applicable)

(6) airplane zero-fuel gross weight

(7) cruise altitude

### 4.4.2 AIRPORT/PATH VERIFICATION

The default combination of destination airport, profile descent procedure or STAR, and runway provided during preflight is assumed unless changed by pilot input. The navigation data base will contain alternative procedures at the selected airport as well as other airports with applicable paths. Selection of airport, meter fix, and runway will be sufficient to cause insertion of an alternate descent procedure. The procedure will be displayed waypoint by waypoint on the CDU for pilot review: waypoint sequence,

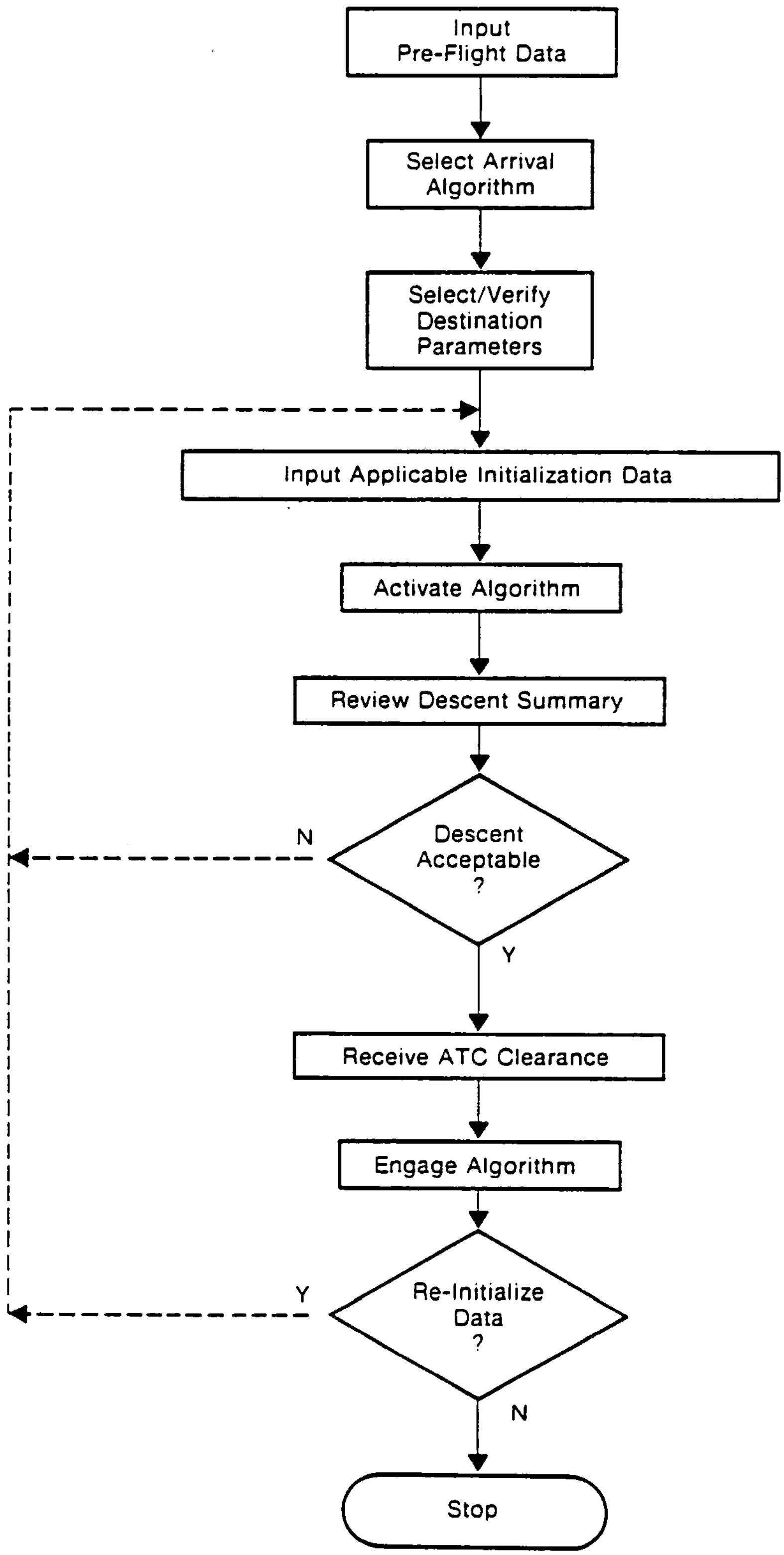


*Figure 9. Sequence of Pilot Inputs and Actions*

*Table 1. Pilot/Avionics/Data Base Input Specifications*

| Function | Default (Internal) | Source | Pilot Input Via CDU |
|---|---|---|---|
| (1) Selection of arrival algorithm | ----- | ----- | Selection |
| (2) Destination airport | Pre-flight loaded airport identifier | Pre-flight information file | ----- |
| (3) Profile descent path (approach and runway) | Pre-flight loaded meter fix-runway | Pre-flight information file | Alternate path |
| (4) Icing indication | No icing anticipated | ----- | Icing anticipated |
| (If icing anticipated:) | | | |
| $N_1$ selection | 55% $N_1$ | ----- | Alternate $N_1$ setting |
| Vertical region | 20,000 feet to surface | ----- | Upper and lower altitude limits (MSL) |
| (5) Metering indication | No metering | ----- | Metering in operation |
| (If metering in progress:) | | | |
| Meter fix specification | Pre-flight selected meter fix | Pre-flight information file | Revised meter fix |
| Meter fix time | Pre-flight loaded MFT (if available) | Pre-flight information file | Revised ATC-assigned MFT |
| (6) Holding indication | No holding anticipated | ----- | Holding anticipated |
| (If holding:) | | | |
| Holding fix specification | Published fix for selected path | Navigation data base | Alternate fix outbound of meter fix |
| Inbound holding magnetic course | Inbound course of published holding fix for selected path | Navigation data base | Course of alternate holding fix inbound leg |
| Turn direction | Published direction | Navigation data base | Opposite direction |
| Holding mode selection | ----- | ----- | Stacking, ATC-assigned altitude, or fuel-efficient altitude holding selection |

*Table 1. Pilot/Avionics/Data Base Input Specifications (Continued)*

| Function | Default (Internal) | Source | Pilot Input Via CDU |
|---|---|---|---|
| (If stacking:) | | | |
| Stack altitudes | ———— | ———— | Top/bottom altitudes (MSL) |
| (If ATC-assigned altitude:) | | | |
| Assigned altitude | ———— | ———— | ATC-assigned altitude (MSL) |
| (NOTE: If minimum-fuel altitude holding (paragraph 4.4.3.3) is assumed, algorithm will compute the holding altitude.) | | | |
| Expected delay | ———— | ———— | Delay (minutes, seconds) |
| Holding airspeed | Recommended speed at holding altitude (if stack, bottom altitude) | Airframe data base | Alternate airspeed (kcas) |
| (7) Algorithm activation | ———— | ———— | Activation |
| (8) Current position | ———— | Latitude and longitude from IRS; altitude from ADS | ———— |
| (9) Current gross weight | [Pre-flight loaded zero-fuel weight] + [current fuel] | Zero-fuel weight from pre-flight information file; fuel remaining from fuel totalizer | ———— |
| (10) Current time | ———— | Internal clock | ———— |
| (11) Current speed | ———— | Air data system | ———— |
| (12) Entry fix Mach | Current cruise Mach | Speed recorded at present position (Item 11) | ———— |
| (13) Entry fix gross weight | [Gross weight from Item (9)] - [predicted fuel burn after 5 minutes] | Fuel flow from engine data base | ———— |
| (14) Entry fix position | [Current lateral position] + [elapsed distance after 5 minutes]; altitude same as present altitude | Altitude recorded at present position (Item 8) | ———— |
| (15) Entry fix time | ETA based on current time + 5 minutes | Time recorded at present position (Item 10) | ———— |

*Table 1. Pilot/Avionics/Data Base Input Specifications (Concluded)*

| Function | Default (Internal) | Source | Pilot Input Via CDU |
|---|---|---|---|
| (16) Weather model computations | Pre-flight loaded wind and temperature forecasts adjusted by cruise measurements | Forecasts from input file. Cruise wind from IRS. Temperature at cruise from air data computer | ---- |
| (17) (If holding or path-stretching required:) | | | |
| (Holding: same input session as Item 16) | | | |
| (Path stretching:) | | | |
| Offset starting point | ---- | ---- | Lateral position |
| Lateral offset limit | 10 nmi | ---- | Alternate offset limit |
| Turn direction | Right | ---- | Left |

courses, distances, altitude and profile descent speed restrictions, aimpoint (outer marker) speed, airport elevation, and published holding and meter fix identification. Prior to algorithm activation, the pilot may make any required changes to the flight plan. The revised path may be converted to the active flight plan by appropriate pilot action on the CDU.

### 4.4.3 PATH INITIALIZATION

These data determine the unique characteristics of a descent under given procedural and climatological conditions. If any algorithm default value needs modification, the alternate value is entered on the CDU by the pilot. This interactive session constitutes the bulk of any required pilot inputs. The default operational assumptions are as follows:

(1) no icing

(2) no metering

(3) no holding anticipated

These inputs as well as those of paragraph 4.4.2 can be made at any time prior to activating the algorithm.

#### 4.4.3.1 Icing

The default assumption is that an icing condition is not anticipated throughout the descent. Changing the default causes the icing page to be displayed. The icing default values are:

(1) 55 percent $N_1$ (for engine anti-ice)

(2) icing region between 20,000 feet MSL and the surface

but may be modified via the CDU.

#### 4.4.3.2 Metering Indication

The default status is □no metering.□ If the metering page is called up, these defaults then are displayed:

(1) nominal meter fix of the descent path selected

(2) preliminary meter fix time (if provided)

Changes must be made on the CDU.

#### 4.4.3.3 Anticipated Holding Indication

The default assumption is that no ATC holding is in effect. When the default is changed, the holding page is subsequently displayed, with the following holding defaults assumed:

(1) published holding fix for selected path

(2) published holding fix magnetic course

(3) published turn direction

Changes to any default are made on the CDU. Any waypoint outbound of the meter fix may be selected as the holding fix. Also, on the same page, the holding mode selection must be made:

(select one:)

(1) stack holding (multiple-airplane holding)

(2) ATC-assigned holding altitude (single-airplane holding)

(3) minimum-fuel holding altitude (single-airplane holding)

The minimum-fuel holding altitude is the holding fix altitude intersecting the minimum-speed descent path. After completion of this page, the display will request the following, depending on the holding mode selection:

(for stacking:)

(1) top and bottom stack altitudes (MSL)

(2) anticipated delay (minutes, seconds)

(for ATC-assigned altitude:)

(1) assigned altitude (MSL)

(2) anticipated delay (minutes, seconds)

(for minimum-fuel altitude:)

(1) anticipated delay (minutes, seconds)

Anticipated delay is used by the algorithm to help estimate an aimpoint gross weight. The algorithm will calculate the fuel-efficient altitude after the algorithm is engaged. Holding speed will be a function of the holding altitude. In a holding stack, the speed is based on the bottom altitude.

The case of pilot-initiated holding required to absorb excess ATC delay is handled in paragraph 4.4.9.

### 4.4.4 ALGORITHM ACTIVATION

After all input requirements are met, the pilot will activate the algorithm on the CDU to calculate the descent path. No further pilot inputs are required, unless the algorithm cannot compute the path within the aeroperformance limits of the airplane.

Prior to the entry fix, five minutes are allowed for the algorithm to complete the descent path calculation and display results, the pilot to request a clearance from ATC, ATC to issue its clearance, and the pilot to engage the algorithm. The algorithm should be provided with present position data (latitude and longitude) by the inertial reference system, current speed and altitude by the air data system, and current time by the internal clock. Current gross weight can be computed by adding the zero-fuel gross weight provided during preflight and the current fuel totalizer reading. These values are used to predict airplane state at the entry fix.

There is some latitude as to when the algorithm can be activated. However, because the entry fix is positioned at a fixed time interval in the future, the moment of algorithm activation should not be so far in advance that the cruise wind and temperature measurements might be significantly different than those at the top-of-descent (TOD). Nor, in the case of a metered descent, should it be so late that a spoiler descent would be required to meet the time objective.

The activation window might be determined based on prior experience or calculation and referenced to an average clean-idle descent time to the meter fix (if a metered descent) or to a fixed distance from the airport.

### 4.4.5 ENTRY FIX CONDITIONS

Speed and altitude at the entry fix are assumed to be the airplane speed and altitude at the time of algorithm activation. Entry fix gross weight is calculated by subtracting from the current gross weight the expected fuel burn over five minutes. Fuel burn rate and the number of engines are obtained from the engine and airframe data bases, respectively. The entry fix position is determined by the elapsed distance over five minutes and the current cruise speed.

### 4.4.6 WEATHER MODEL COMPUTATIONS

The wind and temperature forecasts, provided either during preflight or revised en route, are updated by current cruise wind and temperature, as described in paragraph 4.1.4. Current wind is supplied by the inertial reference system (IRS); current static air temperature is computed by the air data system (ADS). No pilot inputs are required. If no forecasts are supplied, the wind model is assumed to be the wind measured at cruise altitude, decaying linearly to zero on the ground.

### 4.4.7 SPEED TRANSITION MODEL CONSTRUCTION

The speed transition model (Mach to CAS) requires the determination of the airplane low- and high-speed limits, primarily as a function of gross weight, as described in paragraph 4.1.6. The low-speed limit at the maximum service ceiling altitude (35,000 feet for the 737-100) is the maximum of the procedural flap extension speed and low-speed Mach buffet. The high-speed limit is the minimum of the high-speed Mach buffet, maximum operating true airspeed, maximum operating Mach, and thrust-limited speed. The service ceiling altitude and all the speed limits are to be obtained from the airframe data base.

### 4.4.8 RUNWAY AND HIGH PROFILE CONSTRUCTION

The segment calculation modules, whose functions are described in greater detail in Reference 2, employ airplane, navigation, weather, and engine data. Engine data consist of idle thrust fuel flow versus Mach (and altitude); non-idle fuel flow versus normalized thrust (and Mach and altitude); idle thrust versus

Mach (and altitude); engine pressure ratio (EPR) versus corrected $N_1$ (and Mach and altitude); installed net thrust versus EPR (and Mach and a thrust correction as a function of Mach and altitude); maximum climb EPR versus total air temperature (TAT); and maximum cruise EPR versus TAT. Airplane data are low-speed and high-speed performance envelope speed limits, both as a function of weight and altitude; maximum spoiler drag coefficient versus equivalent airspeed; drag polars; number of engines; maximum rate of descent; and wing area. Airplane, navigation, and engine data are to be available from the data base.

### 4.4.9 REQUIRED DELAY

When the algorithm determines that increased path distance is required to make good a meter fix-time assignment, additional pilot inputs are needed depending upon the delay mode selected by the algorithm.

#### 4.4.9.1 Holding Mode

The inputs are the same as described in subparagraph 4.4.3.3, except that no input is required (appropriate) for anticipated delay, since the algorithm computes the delay.

#### 4.4.9.2 Path Stretching Mode

Path stretching is assumed to be carried out at cruise altitude, prior to the TOD. The pilot needs to specify the lateral position at which path stretching is to begin, the initial turn direction, and the maximum lateral excursion from the nominal path. The last input will most likely be the result of an ATC clearance (10-nautical mile (nmi) offset is the default value assumed by the algorithm). The algorithm will automatically adjust the time between the entry fix and TOD by the amount of path-stretching delay.

## 4.5 PATH REVISION REQUIREMENTS

Changes in the ATC environment may require another path calculation to satisfy new constraints. The value of this aspect of an on-board flight management computer system will depend on the expediency with which both the pilot can define new inputs and the algorithm can consequently redefine the path after the appropriate ATC clearances have been issued. The required changes must be known far enough in advance to allow adequate time for the pilot to enter the new input dataset. Algorithm reinitialization is depicted as part of the processing flow in Figure 2 and the sequence of pilot inputs in Figure 9.

A reinitialization capability must provide the required flight management computer (FMC) interfaces to disengage the previously engaged path and evaluate the greater restrictions placed on the path-definition process as the airplane approaches the meter fix. On reinitialization, the airplane must transition from the old engaged path and meter fix time (MFT) to a new path and, possibly, time. The significant impact on making good the (new) MFT must be considered, since the available time delay margin and distance will have shrunk.

For a metered path, any path revision will decrease the probability of making good the MFT. The algorithm will search for another speed schedule to stay within the original time constraint while still conforming to airplane performance and ATC restrictions. If no speed schedule will satisfy the time requirement, a new time must be assigned by ATC to continue metering.

Several operational situations will prompt the use of path (and time) revision options. The development of a weather cell or clear air turbulence zone may require circumnavigation by selecting a different arrival path, or flying a modification to or lateral offset from the nominal arrival path. Where traffic permits, the options may be exercised to delete a waypoint, fly direct to another waypoint, or eliminate altitude and speed restrictions. Nonstandard situations may require the use of a lateral offset, arrival path modification, "direct to," waypoint deletion, or altitude and speed constraint change options. The lateral offset feature can be used when ATC approves overtaking a slower airplane.

When an unexpected system delay arises, the airplane may have to hold, fly a lateral offset (path stretch), or be assigned a new MFT. The algorithm decision logic must take into consideration the following:

(1) If a MFT is assigned when no metering was previously in effect, or if a later time assignment is made to supersede the original one, a (new) speed schedule should be computed. If a slow-speed schedule cannot satisfy the time constraint, then holding or path stretching may be needed.

(2) If stack holding is already in effect and the airplane is not holding yet, then new holding parameters can be calculated based on the new MFT.

(3) If stack holding is already in effect and the airplane is in the stack, a procedure should be defined for incorporating the extra required delay into the remaining holding path after the next holding fix crossing (the timing reference, as mechanized in the LFM/PD holding logic).

(4) If stack holding is already in effect and the airplane has just left the stack, speed recalculation, waypoint insertion, or path stretching (lateral offset) may be required.

### 4.5.1 LATERAL PATH REVISION

The algorithm capability should be extended to include changes in the descent phase of the lateral flight plan.

Lateral path revision capabilities may take the form of a change in the destination airport, a change of the profile descent path (different approach, including new meter fix or meter-fix outer-marker combinations), partial modifications to the nominal descent path, changes at a waypoint, and flying lateral offsets. The following sections also indicate applicability to three-dimensional (3D) and four-dimensional (4D) path-prediction modes.

#### 4.5.1.1 Airport Change

Normally, at the time the descent algorithm is to be initiated, an airport change would not be required by ATC or the pilot. Therefore, this capability should be exercised during prior flight phases.

#### 4.5.1.2 Arrival Path Change (3D and 4D)

The navigation data base will contain alternative paths at a profile descent airport. If an arrival path change is invoked sufficiently ahead of the TOD, the algorithm can accommodate the modification. However, once descent has begun, the algorithm must be reinitialized, and the new path must be specified as in subparagraph 4.5.1.3. For a 4D descent, when the new arrival path has another meter fix, a new MFT must be specified.

#### 4.5.1.3 Partial Changes to Descent Path (3D and 4D)

When the algorithm is reinitialized, the flight plan modification input procedure will be required. Another entry fix will be defined by the algorithm. For a timed descent, the meter fix is assumed to remain the same, otherwise an arrival path modification is implied (subparagraph 4.5.1.2).

#### 4.5.1.4 Changes at a Waypoint (3D and Some 4D)

The algorithm should make provisions to allow changes at a designated waypoint. These modifications could include inserting or deleting a waypoint, requiring holding at the waypoint, and specifying a "direct to" leg to another waypoint. The algorithm must be reinitialized and the required change made directly on the flight plan CDU display page. Time-based descents may use the waypoint insertion or holding path modification options.

#### 4.5.1.5 Lateral Offset (3D and 4D)

In a lateral offset feature, the pilot must specify the waypoint or lateral position at which the offset is to begin, the offset distance, and turn direction of the offset from the waypoint or lateral position. The input procedure is the same as that for specifying path-stretching parameters. The waypoint selection will be among those defined in the navigation data base; the lateral position specification (phantom waypoint) will include its latitude and longitude or its radial and distance from a navigational aid or other defined waypoint. The airplane will continue flying a lateral offset path until the pilot, via the CDU, commands either a return to the nominal path or a "direct to." Otherwise, the algorithm could cause the airplane to return automatically to the original path at the waypoint prior to the runway outer marker. For a 4D descent, the complete offset path must be specified by the pilot.

### 4.5.2 VERTICAL PATH REVISION

Vertical path revision capabilities include changing programmed ATC waypoint altitude and speed constraints. In addition, when the airplane makes an early or late TOD, a method for computing a new or partial path will be required.

#### 4.5.2.1 Changes to Altitude Constraints (3D Only)

Changes to altitude constraints include changing or deleting existing constraints. No additional vertical path modification capability is required when altitudes of stored waypoints are used in a lateral path revision, since altitude constraints at these waypoints are contained in the data base.

#### 4.5.2.2 Changes to Speed Constraints (3D Only)

The capability to modify speed constraints should be provided to accommodate emergency or traffic-free descents. The option to change or eliminate the constraint at an individual waypoint or eliminate the limits at all waypoints in the descent flight plan will be available.

#### 4.5.2.3 Early or Late TOD (3D and 4D)

If the TOD position has to be changed, the algorithm must be capable of computing the new descent path segment to capture the nominal path or, when metering is in effect, to determine a new speed schedule employing thrusted or spoiler segments. The above capability may require the new TOD position to be supplied by the pilot prior to the descent.

### 4.5.3 MFT REVISION

Changes to the MFT assignment should be accommodated to extend the 4D capability of the algorithm. If a change can be incorporated prior to the new TOD, then the new path can usually be determined by a new speed schedule (with a possible delay path). If the MFT is changed after the airplane has begun its descent, then the problem becomes one of redefining a new path from some future waypoint inbound.

# 5.0 AIRBORNE ALGORITHM IMPLEMENTATION

The current status of the airborne algorithm implementation effort is detailed in this section. This effort in its entirety requires reduction of the working core size by overlay management, the integration of path revision capabilities recommended in subsection 4.5, and the representation of the man-to-machine inputs and machine-to-machine data interfaces that are specified in subsection 4.4. The overlay task was undertaken first in order to partition the algorithm functionally. Preliminary testing on the reduced-core algorithm was completed. The recommended path revision capabilities not yet implemented are discussed in subsection 5.2. The input structure integration task has not been initiated.

## 5.1 ALGORITHM ENHANCEMENTS AND EXTENDED CAPABILITIES

Additional capabilities and design enhancements beyond those described in Reference 2 have been added to the fast-time LFM/PD baseline algorithm to provide more flexibility to an airborne algorithm. Significant reductions in program execution times were made possible after conducting an algorithm sensitivity analysis.

The meter fix designation can now be given to any waypoint and does not need to be collocated with the first waypoint where an arriving airplane must comply with a speed constraint. The first speed waypoint is now designated as the transition fix and defines the boundary between the high and runway profiles, which are described in paragraph 4.1.7.

The distance over which a required change of speed is constrained by the algorithm has been expanded to include more than one published waypoint. This capability allows greater changes of speed and makes maximum use of the time delay margin available in the flight envelope. Change-of-speed segments are typically required to make the transition from a descent speed to a procedural speed constraint at the meter fix and from the entry fix speed to a descent speed.

Spoiler drag calculations are permitted, when applicable, over more than one segment in order to satisfy an altitude constraint. The algorithm normally assumes a clean airplane configuration (and idle-power thrust) throughout the descent. In the process of the descent path construction from the meter fix up to the entry point, it may not be possible for the last descent segment to make the final altitude constraint even with full spoilers. The algorithm then includes as many preceding descent segments as required to complete the descent with spoilers.

In the previous fast-time algorithm version, performance data were integral files of the program. Airport geometry data were read in as part of each run. The algorithm architecture has been redesigned to store both performance and airport geometry data out of core. The structures of these data are described in subsection 4.3. Data segregation from the functional aspect of the program is a significant step toward developing an airplane-independent algorithm, inviting application to other airplane types.

Significant reductions in algorithm execution time were achieved as a result of changes tested and validated by a sensitivity analysis. Alternative mechanizations to the 4D speed schedule search (to make good an assigned MFT) and spoiler and thrust factor computations were incorporated. Execution-time benefits were also derived from increased path segment integration step sizes. These changes produced no significant differences in time, distance, and fuel values, while reducing mainframe computer (CYBER) execution time by at least 70 percent for a variety of descents.

The speed schedule (Mach/CAS combination) to make good a MFT was originally determined by using the binary search technique in which the descent Mach was varied and the resultant descent time compared to the required descent time. The current implementation computes the trial descent Mach from an iteratively adjusted, linear model of delay (descent time) versus descent Mach. In each iteration, a linear delay versus Mach relationship is constructed from the previous test Mach and its associated delay and one of the limits of the previously constructed model. The Mach-to-CAS transition point is determined by the speed transition altitude model.

Analogous search techniques were used to calculate the spoiler and thrust factors computed for segments requiring above-idle thrust or spoiler drag, respectively. In either case, a clean-idle configuration is insufficient to effect the descent given the ATC constraints at the two waypoints. A faster converging solution to the required factor is possible if a linear relationship is assumed between spoiler or thrust factor and resultant altitude. Then, the target altitude can be used to compute a trial factor. The trial factor altitude at the end of the segment computation will then be compared to the target altitude. If the difference is outside the acceptance criterion, then another factor versus resultant altitude model is constructed between the trial factor-altitude data point (just tested) and the appropriate boundary point of the previous model. The iteration is continued until an acceptable final altitude is obtained.

In the calculation of the thrust factor, the initial model boundary points are taken to be the percentage of maximum cruise thrust required to maintain level flight and idle thrust (FACTOR = 0) with their associated altitudes. The initial spoiler factor model is constructed between maximum spoiler deployment and a clean-idle configuration.

Each segment of a descent path calculation is constructed by integrating a sequence of intervals comprising the segment. A level segment calculation does a step-wise integration over time and solves for fuel, elapsed time, and (if an acceleration or deceleration segment) final speed over a given distance. A descent segment calculation changes altitude and solves for fuel, elapsed time, and (if a clean-idle descent segment) distance to a point-of-descent. The sensitivity analysis indicated that a significant trade of interval step sizes against execution time can be made without compromising the high profile descent time estimation accuracy. From the original 10 seconds for a level segment and 100 feet for a descent segment, iteration step sizes were increased to 50 seconds and 500 feet, respectively.

## 5.2 INITIAL DESIGN IMPLEMENTATION

The problem of apportioning the path definition function to 28,000 octal words suggests an overlay design as one possible solution. Memory management is another option. The final technique will be decided depending on operating system support for the Norden computer. The overlay design is presented here to illustrate the partitioning, which can be used to carry out the descent profile prediction function. The modular architecture of the algorithm lends itself to overlaying. However, execution time is increased as the number of overlay segments is increased, because inactive modules stored on disk must be retrieved as needed.

The overlay design distinguishes between those modules, which are always resident in core (the root), and those required on an individual or sequential basis (the branches). The root modules consist of, or perform, the following:

(1) Coordination of the path-prediction function (executive routine).

(2) Physical and unit conversion constants.

(3) Storage of most recently calculated path parameters in mass storage devices.

(4) Validation (via CDU) of input data.

(5) Calculation of linear regression models.

(6) Determination of a waypoint's numerical order.

(7) Computation of the speed transition (Mach to CAS) altitude.

(8) Calculation of fuel consumption during level flight over a specified time interval.

(9) Conversion of speeds to those based on a different reference.

(10) Determination of the gas law variables.

(11) Computation of wind speed and direction and of ambient temperature.

(12) Calculation of drag force.

(13) Calculation of thrust force.

(14) Computation of fuel flow.

(15) Calculation of the slow- and fast-speed limits.

(16) Conversion of altitudes to those based on a different reference.

The branch architecture divides the remaining logic into four sub-functions, which are executed in sequence:

(1) Data initialization and preliminary path processing.

(2) Path calculation.

(3) Evaluation of the path calculation.

(4) Display of acceptable path.

This sequence satisfies the processing flow requirements in subsection 4.1. Each branch in turn may be separated into sub-branches. This process can be continued down to many levels, although at the expense of execution time. For example, the calculation of the holding delay path consists of five levels. Figure 10 illustrates the overlay architecture. A selection to be made by the overlay logic is represented by parentheses enclosing a list of the candidate modules that are grouped as one overlay branch. Underscored names represent a group of functionally related routines, which are listed elsewhere in the figure. Groups of library routines are delimited by colons. All module functions are summarized in Appendix B.

| | |
|---|---|
| | LFMPD—BLKDAT—GENERL—SPEEDS—PERFRT—(PRFCLC,PROFIL,EVPRF, DISPLY) |
| GENERL: | STRPTH—STRNII—VALDTE—LINREG—NWPIDF—HCRIT—CRFUEL |
| SPEEDS: | PRFLIB/LB:TMACH:CAS:CMACH:TAS:GNDSPD:GTAS:DRIFT:AWCMP |
| PERFRT: | ATMFXN—MODELS—PERFMN—ALTCON |
| BLKDAT: | FILES—CONST—CONTRL |
| PRFCLC: | RDCALT—(CALMDL,RLOAD,INITL) |
| CALMDL: | ATMOS—ADDTRP—CONVRT—CORCPT—CORCPW—GTFCST—LINMDL—FCSTKW—FCSTKT |
| RLOAD: | LOADAR—(RLOAD1,RLOAD2) |
| RLOAD1: | WEIGHT—READIN—GTPRF—RVGEOM—ALTSPD—ERRAS—VLDAS—ROUTE—ERRRTE—VLDRTE |
| RLOAD2: | IDTFWP—ASGNV—CSFIX—ASGNA—CONTPA |
| INITL: | ICESET—STGWT—HCCALC |
| PROFIL: | EXCCAP—RODALT—(RWYPR,HIGHPR) |
| RWYPR: | RWYPF—SEGCLC |
| SEGCLC: | ITYPE—SEGCAL—(SEG1,CHGSPD,DECNT) |
| CHGSPD: | REMOVE—(CHEFA,CHEFD,CHACC,CHDEC) |
| CHEFA: | EFACC—SEG3—(ADJA1,ADJA2) |
| CHEFD: | EFDEC—SEG2—ICING—(ADJD1,ADJD2) |
| CHACC: | ACCEL—SEG3—(ADJA1,ADJA2) |
| CHDEC: | DECEL—SEG2—ICING—(ADJD1, ADJD2) |
| DECNT: | SEG4—(RINSRT,SEGDC,SEGAC,DTSEG) |
| RINSRT: | INSPOD—INSRTT—INSERT |
| SEGDC: | SEG4DC—ADJTLD—DCTTLS—ICING—(ICPER,TSTPER) |
| SEGAC: | SEG4AC—ADJTLA—DCTTLS—ICING—(ICPER,TSTPER) |
| DCTTLS: | DSAS—PFCAS—DCTTOT |
| DTSEG: | (RDSEG,RTSEG) |
| RDSEG: | DSEG4A—DSEG4B—DSEG4I—(DFCTMX,DSEGC,SPOILF,NIREC,VAREC) |
| DSEGC: | DSEG4C—PFCAS—(ICING,DSAS,DGPER,DCTTOT,ADJTLD,RODEND) |
| DGPER: | (DGPERT,DGPERI) |
| RTSEG: | TSEG4A—TSEG4B—THRSTF—ADJTLD—DCTTLS—THPER—NIREC |
| HIGHPR: | HIGHPF—ETIME—HPRCLC—(METER,DELAYS) |
| HPRCLC: | DESCAS—COMPCI—DMACH—SLMACH |
| METER: | TIME—IDMFWP—FAMACH—MSRCH—RDMTRS—RDMFT—TIMERQ—HICLC |
| HICLC: | HPD—SEGCLC |
| DELAYS: | DELAY—PSMTRF—TREV—(INFO,HOLD,STRTCH) |
| INFO: | HLDINF—HLDALS—HLDSPD—IDHWPT—INSHF—INSERT |
| HLDALS: | HLDNOA—HLDOA—HLDSTA—HLDSA |
| HOLD: | HLDPRF—(RVPTH,HLDPRO,STACK) |
| RVPTH: | RVPATH—BSACOS—HEWPT—HFIPA—TSACOS—INSRTT—INSERT |
| HLDPRO: | HPRHLD—SEGCLC |
| STACK: | STINF—HDWND—HLDALT—NUMCIR—STPTRN |
| STPTRN: | STPAT—(HDCNT,LEGS,TURNS,HALTM) |
| HALTM: | HALTMF—BNKANG |
| HDCNT: | DCTHA—DSAS1—DCTTOT—ADJTL1—ICING—(ICPER,TSTPER) |
| LEGS: | TLEG1—TLEG2—GAMMA |
| TURNS: | TTURNS—TREVA—TREVB—AALPHA |
| STRTCH: | PATHST—PSOFST—RVPAPS—INSRTT—INSERT |
| EVPRF: | ATCAPP—EVGWT |
| DISPLY: | REPORT—IROUND—DETDIS—SUMDIS |
| DETDIS: | NUMID— PDDIS— CONMSL—DETHLD—DISDTI |
| SUMDIS: | SUMARY—SUMDLY—SEGTOT—MSEC |
| ATMFXN: | PRFLIB/LB:DELTA:RHO:SIGMA:THETA |
| MODELS: | PRFLIB/LB:IALTM:WNDSPD:WNDDIR:TEMPC |
| ALTCON: | TRUALT—CMSLPA—PAMSL |
| PERFMN: | RDRAG—THRUST—FUEL—PRFLIB/LB:VFAST:VSLOW |
| RDRAG: | PRFLIB/LB:CDCL:CDSPLR:DRAG |
| FUEL: | PRFLIB/LB:FUELFI:FUELFL |
| THRUST: | PRFLIB/LB:ALTC:EPR:THRSTN:TSTIDL:TSTMCL:TSTMCR:TSTPAR |

*Figure 10. Airborne LFM/PD Overlay Architecture*

## 5.3 RECOMMENDED PATH-REVISION CAPABILITIES

The algorithm currently has a general path-revision capability that allows interactive input changes to be made in the fast-time algorithm. These changes represent the input modes of the airborne version. The capability is invoked when changes are required to the currently loaded inbound path (but not to the default destination airport). Its basic format is the specification of new path segments and their associated constraints from the innermost (closest to the aimpoint) waypoint outbound. An electronic horizontal situation indicator (EHSI) is assumed to aid the flight crew in viewing the airplane's current position in relation to the waypoints along the intended route of flight.

First, the innermost path segment to be retained is identified. The algorithm then requires the names of all waypoints (published or pilot-defined) outbound that constitute the new sequence of waypoints. The last input waypoint is considered to be the new entry fix. Then, after the waypoint input session, the corresponding segment-magnetic courses and distances are required, followed by the maximum and minimum altitude and airspeed constraints at all inclusive waypoints. The algorithm automatically checks the validity of all inputs, consisting of the following:

(1) All magnetic courses must be between 0 and 360 deg inclusive.

(2) All segment distances must be greater than zero nmi but less than a predefined maximum distance.

(3) All altitude constraints (both maximum and minimum) must be greater than zero ft but less than the service ceiling altitude.

(4) All speed constraints are zero knots calibrated airspeed (kcas) or greater, but less than the fast-speed performance limit at cruise altitude for the current airplane weight.

(5) The minimum altitude constraint at a waypoint must not exceed the maximum altitude constraint.

(6) The maximum or minimum altitude constraint at a waypoint cannot be higher than the corresponding one at the next outbound waypoint where a constraint is specified.

(7) The speed constraint at a waypoint cannot exceed that of the next outbound waypoint where a constraint is defined.

The algorithm allows corrections to be made in case of erroneous inputs.

The change procedure now implemented requires some improvement in convenience. It should be possible, for example, to change altitude and speed constraints at a waypoint, delete a waypoint, or specify a lateral offset without the complex procedure described above. Function keys on a CDU are assumed to permit access to the appropriate input modes. The above procedure is also inappropriate when a tactical command is required to change direction immediately, such as "direct to," "fly a specified heading," or "hold at present position." Expediency precludes a time-consuming input process but should not diminish the advantages of computing a time-controlled profile, which requires a well-defined entry fix.

The following subsections discuss recommended additional path-revision capabilities. It should be noted that a waypoint required as an input may be specified in one of three ways.

(1) Name of the published waypoint can be given. Its location (latitude and longitude) is pre-stored in the navigation data base.

(2) Latitude and longitude of a waypoint not contained in the navigation data base can be specified. A name (alphanumeric string) will be assigned by the computer or can be entered by the pilot via the CDU.

(3) Radial and distance from an input navigational aid or any waypoint stored in the navigation data base can be defined. The location of the navigational aid is pre-stored in the navigation data base. The waypoint name will be pilot-entered or computer-assigned, and its latitude and longitude computed.

### 5.3.1 AIRPORT CHANGE

This capability is already assumed to be part of the general FMC software capability. The algorithm currently asks for an airport selection and then a selection of a profile descent path for that airport. Table 1 (subsection 4.4) suggests that the airport and path selection be entered by the flight crew prior to departure from the origin airport (preflight processing). This requires that the initialization process in the algorithm be restructured to display the default destination airport and ask for pilot confirmation.

### 5.3.2 ARRIVAL PATH CHANGE

This revision option is to be used when a different meter fix than the current one is required. If another airport selection is made, the chosen descent path must be specified accordingly. If another descent path at the same airport is needed, the current version of the algorithm should be restructured to display the default path and ask for pilot confirmation prior to an input procedure handling the change.

### 5.3.3 CHANGES TO THE LATERAL DESCENT PATH

This capability differs from the previous one, since the current meter fix is to be retained. Waypoint insertion, waypoint deletion, waypoint holding, "direct to" path linkage, lateral path offset, and changes to altitude and speed constraints constitute the choices to be provided under this option.

#### 5.3.3.1 Waypoint Insertion

One or more waypoints not contained in the original flight plan may be inserted. This requires the identification of the beginning and ending waypoints of the original flight plan and the specification of the new intervening waypoints. A new waypoint may be specified either by entering its published name (the navigation data base contains its inertial coordinates and ATC constraints, if applicable) or defining the inertial coordinates (the pilot or computer will assign a name). When a new waypoint is defined, any applicable speed and altitude constraints also should be specified.

#### 5.3.3.2 Waypoint Deletion

The waypoint deletion option refers to removing one or more waypoints from the flight plan and is to be differentiated from a "direct to" function. The currently implemented path-revision function can effectively perform this capability by defining the new flight plan, waypoint by waypoint, but omitting the waypoints to be removed. The input procedure would be greatly simplified, however, if the waypoints to be deleted could be named.

#### 5.3.3.3 Waypoint Holding

Holding can be conducted at a future waypoint (either published or pilot-defined) or at present position. Note that there is an operational distinction between this type of holding and that generated by a 4D airplane to absorb ATC delay. The latter is described in detail in Reference 2. The required-pilot inputs, to hold at a future waypoint, consist of the name of the holding fix, entry altitude, holding speed, and turn direction. When holding at present position is activated, the algorithm assumes that present position is the holding fix, the current altitude is the entry altitude, current speed is the holding speed, and right is the turn direction.

#### 5.3.3.4 "Direct to" Waypoint

The "direct to" function is used for tactical reasons (safety, avoidance of bad weather or path shortening). Its execution changes the airplane path from present position. The lateral navigation function will immediately steer the airplane onto a direct course to the specified waypoint. For this reason, profiles requiring a specific speed schedule to absorb the requisite delay in making good a MFT target will not be generated, although fuel-optimum profiles with no time constraints (no metering in effect) can still be calculated. For reasons of convenience, the "direct to" waypoint should be one already stored in the navigation data base.

#### 5.3.3.5 Lateral Offset

A lateral offset function can be executed immediately or incorporated in a strategic revision to the flight plan. As in the previous option, use of this function as a tactical maneuver will preclude the algorithm from calculating a time-controlled profile. For expediency, the flight crew input should consist only of an offset distance and direction. The lateral path profile should be parallel to the nominal path until a "recapture" command is issued or another path revision function is engaged.

If the offset configuration is known sufficiently ahead of path engagement, flight crew inputs should consist of offset distance and direction and specification of the waypoint at which the offset path is to recapture the nominal path. A time-controlled profile can still be computed when this offset mode is engaged. Any speed and altitude constraints at the bypassed original waypoints are assumed to apply at their paired offset waypoints.

### 5.3.4 Changes to the Vertical Descent Path

These types of changes include altitude constraint modifications, speed constraint modifications, and adjustments to correct for an early or late TOD.

#### 5.3.4.1 Changes to Altitude Constraints

Modifications at waypoints already part of the flight plan should be made directly on the appropriate CDU display page. Changing constraints at new waypoints should be a part of the waypoint insertion process (subparagraph 5.3.3.1).

#### 5.3.4.2 Changes to Speed Constraints

As in the previous section, the speed constraint may be changed at an existing waypoint directly on the CDU or be made as part of the waypoint insertion process (subparagraph 5.3.3.1).

#### 5.3.4.3 Corrections for Early or Late TOD

A new path segment may be required if unpredicted winds are encountered after the original path has been engaged. Depending on whether time control is required or not, changes to the descent path require one of two solutions when the flight management system (FMS) has determined that the descent winds have been incorrectly estimated. For a 3D path, a path segment using added thrust or spoiler drag may be required to intercept the nominal path. When this mode is activated on the CDU, the algorithm will automatically identify the next waypoint. An altitude and speed at the waypoint have already been defined in the previous calculation and will serve as the targets for the revised segment.

For a 4D path, the pilot may activate the algorithm to recompute a new path and speed schedule in order for the airplane to arrive at the meter fix at the originally assigned time.

### 5.3.5 CHANGES TO THE MFT

The new MFT should be entered on the CDU. The algorithm will subsequently compute a new path with a speed schedule appropriate to making good the new time.

# 6.0 SYSTEM INTERFACE REQUIREMENTS

The path definition algorithm described in this document will be one element of an FMS. The algorithm developed is assumed to reside in an FMC and interact with (1) the pilot via the CDU, (2) the lateral path processing module in the FMC, and (3) the guidance and steering module in the FMC. The guidance and steering module will, in turn, interface with the autopilot and autothrottle system. Other path-definition algorithm interfaces will include sensors (air data, IRS, engine instruments, etc.) and off-line navigation, airframe and engine data bases. A schematic of one possible architecture is illustrated in Figure 11. The following interface requirements were assumed in the airborne algorithm design.

## 6.1 CDU INTERFACE REQUIREMENTS

A default set of input options is available for the path-definition algorithm once the destination airport is identified. The path-computation process must be initiated by the pilot and, if desired, engaged. All non-default options for the descent path must be selected from available menus displayed on the CDU. Parameter values, where required, will be requested and must be entered via the CDU. A series of operational scenarios is contained in Appendix A.

Results of the algorithm path-computation process will be presented to the flight crew for review on the CDU. Summarized information, as shown by the examples in Tables 2 and 3, will be available.

Required CDU entries will be minimized, where possible, to provide minimum impact on flight-crew workload.

## 6.2 LATERAL PATH-PROCESSOR REQUIREMENTS

The path-definition algorithm assumes a lateral (x,y) path over the ground in terms of great circle arc segments of defined course and distance and turn circle arcs between great circle arcs. If waypoints are defined in terms of latitude and longitude, a set of equations to convert to course and path distance will be required.

The path-distance equations must consider the turn segments. Implications of ignoring these terms in the calculations are threefold: (1) a path-distance error between waypoints is introduced, (2) an error is introduced in thrust required to maintain level flight, and (3) a ground-speed (here time) error, in turning, is introduced. For the expected range of approach conditions, these errors are significant. The expected path-distance error can be computed as $(2V^2/g \tan \Phi)[\tan (\Delta \psi/2)-\Delta\psi/2]$ where V is ground speed, $\phi$ is the bank angle and $\Delta\psi$ is the course change (in radians). For a 45° course change at 250 kcas at 10,000 feet and a 22.5° bank, the path error will be about .1 nmi.

## 6.3 GUIDANCE AND STEERING REQUIREMENTS

The path-definition algorithm defines the ideal path that the airplane should follow in executing a fuel-efficient descent in a time-based ATC environment. To fly to this path, special guidance laws will be required to interface with the autopilot and autothrottle.

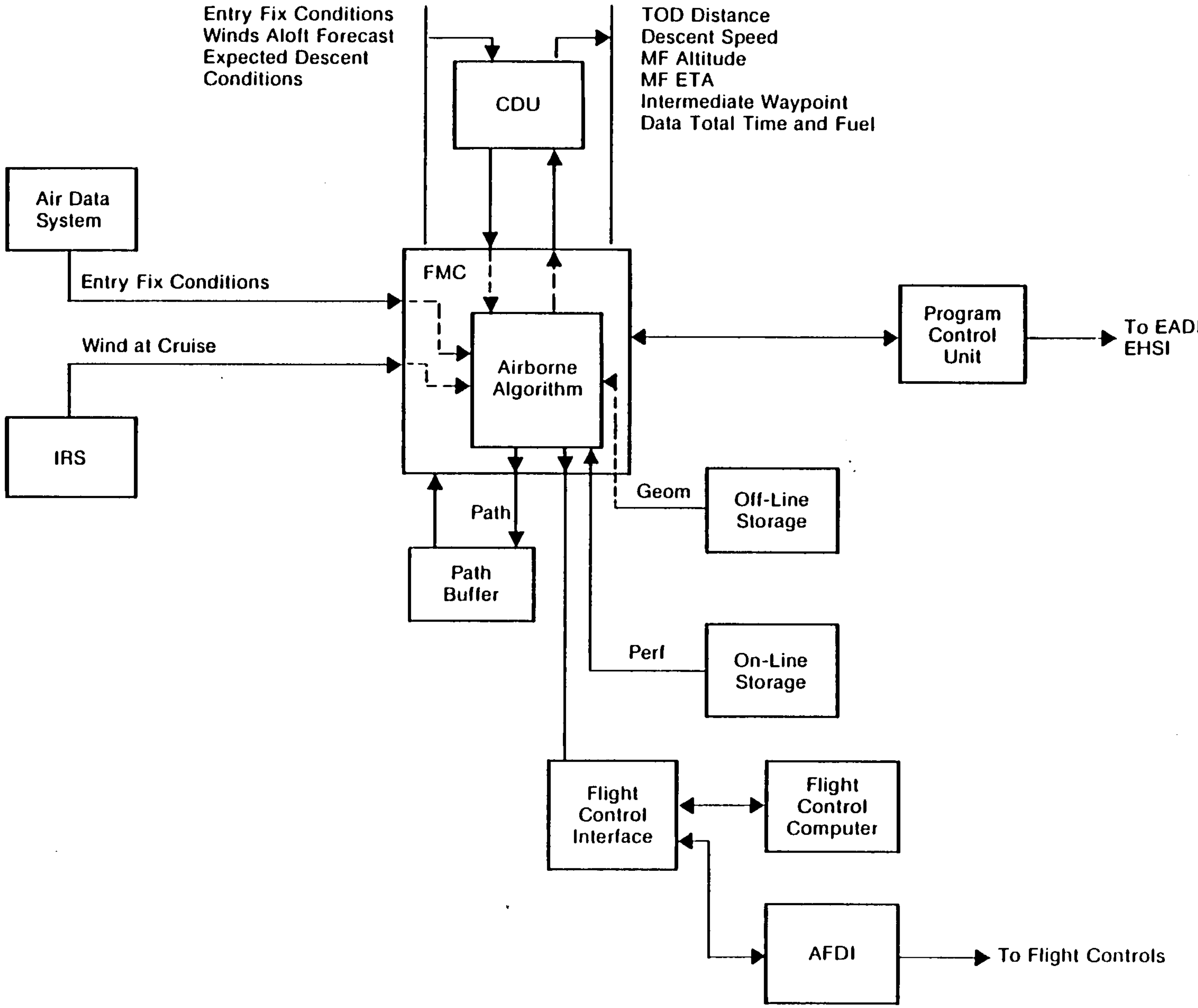


*Figure 11. System Interface Diagram*

*Table 2. Sample Profile Descent Path Array*

| CIVET 25 Profile Descent | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Segment Description | | Mag Course | Distance (nmi) | Time (sec) | Altitudes | | Speeds (CAS) | | Fuel (lb) |
| | | | | | Begin | End | Begin | End | |
| PGS | ECSFIX | 227 | 5.5 | 47.1 | 35000 | 35000 | 259 | 228 | 14.1 |
| ECSFIX | ABREE | 227 | 114.5 | 1051.1 | 35000 | 35000 | 228 | 228 | 1203.9 |
| ABREE | DIKES | 226 | 15.0 | 137.6 | 35000 | 35000 | 228 | 228 | 156.7 |
| DIKES | TOD | 226 | 23.2 | 212.5 | 35000 | 35000 | 228 | 228 | 241.4 |
| TOD | EMMEY | 226 | .8 | 7.7 | 35000 | 34754 | 228 | 229 | 2.3 |
| EMMEY | BAIRS | 226 | 24.0 | 221.8 | 34754 | 26952 | 229 | 250 | 66.5 |
| BAIRS | TP | 226 | 22.0 | 224.7 | 26952 | 19681 | 250 | 250 | 67.4 |
| TP | CIVET | 248 | 8.0 | 88.4 | 19681 | 16771 | 250 | 250 | 26.5 |
| CIVET | ARNES | 248 | 18.0 | 214.2 | 16771 | 10000 | 250 | 250 | 73.4 |
| ARNES | POD2 | 248 | 1.0 | 12.1 | 10000 | 10000 | 250 | 250 | 16.3 |
| POD2 | CSFIX1 | 248 | 7.9 | 100.7 | 10000 | 7000 | 250 | 250 | 41.8 |
| CSFIX1 | BASET | 248 | 2.6 | 37.4 | 7000 | 7000 | 250 | 210 | 15.9 |
| BASET | DOWNE | 248 | 7.3 | 115.3 | 7000 | 4361 | 210 | 210 | 51.1 |
| DOWNE | HUNDA | 248 | 2.8 | 45.3 | 4361 | 3436 | 210 | 210 | 21.5 |
| HUNDA | CSFIX2 | 248 | 3.2 | 52.9 | 3436 | 1892 | 210 | 210 | 26.3 |
| CSFIX2 | LIMMA | 248 | 1.7 | 30.4 | 1892 | 1892 | 210 | 180 | 15.5 |

Descent Requirements

Starting at BASET 21.9 percent of maximum spoiler drag must be added for the segment to DOWNE to maintain the profile

Starting at HUNDA 100.0 percent of maximum spoiler drag must be added for the segment to CSFIX to maintain the profile

*Table 3. CIVET 25 Summary*

| CIVET 25 Summary | |
|---|---|
| Entry Fix | PGS |
| Meter Fix | CIVET |
| Aimpoint | LIMMA |
| Profile Distance | 257.5 nmi |
| **Entry Information** | |
| Cruise Speed .765 Mach (259 kcas) | |
| Change Speed to 228 kcas at PGS | |
| **Descent Information** | |
| Top of Descent 99.3 nmi from LIMMA | |
| Descent Schedule .682 Mach/250 kcas | |
| **Meter Fix Information** | |
| Altitude at CIVET | 16771 |
| Airspeed at CIVET | 250 |
| **Aimpoint Information** | |
| Altitude at LIMMA | 1892 |
| Airspeed at LIMMA | 180 |
| Gross Wt at LIMMA | 82959 LB |
| **Segment Totals** | |
| Total Time: 43 min 19.1 sec | |
| Total Fuel: 2040.7 lb | |

Control objectives in the descent are fourfold: (1) time at the meter fix, (2) altitudes at the aimpoint and intermediate waypoints, (3) airspeeds at the aimpoint and intermediate waypoints, and (4) minimum fuel use.

The guidance and steering functions should accommodate complex descent paths with intermediate level-offs (at constant airspeed or in deceleration), partial-thrusted descents, spoiler-commanded descents, as well as clean-idle descents. A typical path employing clean-idle descents is illustrated in Figure 4.

Guidance and steering should provide the capability to capture the descent path when the descent has begun early or late, when an intermediate level-off is required by ATC, etc.

# 7.0 CONCLUSIONS

The requirements for an airborne version of the LFM/PD algorithm have been specified. Additional functional capabilities beyond those of the baseline fast-time version are needed, primarily to accommodate pilot inputs and path revisions. Greater algorithm flexibility has been developed in allowing metering at any published waypoint, removing previous distance limits over which changes of speed and spoiler drag descents can take place and developing an algorithm that is airplane-type independent. Improvements in program efficiency have been achieved by a faster-converging, descent-speed search technique for metered profiles and by using larger integration step sizes for all path computations.

The feasibility of implementing the airborne algorithm in a restricted-core computer has been demonstrated with the overlay design. The current algorithm version satisfies the requirements of processing flow and data base architectures, as detailed in subsections 4.1 through 4.3. Additional work is required to develop the flight crew interface logic that is recommended in subsection 4.4. The algorithm currently has a path revision capability, but further enhancements have been recommended in subsection 4.4. Work is also needed to incorporate the suggested implementation described in subsection 5.3. These functions define a tactical mode of 4D navigation to supplement the basic strategic mode resident in the current airborne algorithm. Timely responses to changes in the operational ATC environment and to the vagaries of weather are desirable and, in most cases, practicable, while retaining the attributes of time navigability.

# APPENDIX A

## TNAV OPERATION IN THE EN ROUTE METERING ENVIRONMENT

The development of the en route metering program and implementation within the national airspace system (NAS), together with the LFM/PD 4D time navigation (TNAV) capability, suggest the need to consider procedures to exploit these capabilities for the benefit of the ATC system as well as for the equipped airplane. The following scenarios, representing operations in the Denver air route traffic control center (ARTCC), are an attempt to describe the expected operation of TNAV clearances.

Assumptions in the development of the scenarios include:

(1) The en route metering program, as implemented at the Denver ARTCC, is in effect.

(2) No other users are equipped with TNAV systems; current ATC system capabilities are assumed.

(3) Three levels of delay apply for varying traffic loads at Denver. The summary flow management system features and associated clearances for the 4D airplane are listed for low, intermediate, and high levels of delay:

   (a) Low delay: pilot's discretion descent to the meter fix

   (b) Intermediate delay: ATC-assigned time to the meter fix if no conflicts are projected

   (c) High delay: no ATC-assigned times unless aircraft are projected over low-traffic fix.

To develop the alternative level-of-delay scenarios, the KEANN 26 low-profile descent was selected as a baseline. Each scenario was developed assuming the National Aeronautics and Space Administration (NASA) 515 B-737 performance characteristics and KEANN 26 low-profile approach data. The nominal lateral-approach path is shown in Figure 12.

Figure 13 is a diagram, which provides an overview of the logic that illustrates how the 4D airplane could be operated in Denver ARTCC's en route metering system with a minimum of change to the present ground system operation and procedures. The scenario is based on the logic sequence shown.

The equipped airplane will enter the flow management time-based metering system at cruise altitude and speed, and at a distance typically about 150 nmi from the arrival meter fix. The following is a scenario of ATC and airplane actions (A) and communications (C):

ATC: (A) ATC will enter the flight into the metering system. Using an estimated time to reach the meter fix, based on present flight data, ATC will calculate a tentative MFT.

Airplane: (C) "Center, NASA 515 requests TNAV arrival."

Note: Coordination of as many as four control positions (two high-altitude sectors, the low-altitude arrival sector, and the metering position) may be required to accommodate the TNAV arrival request.

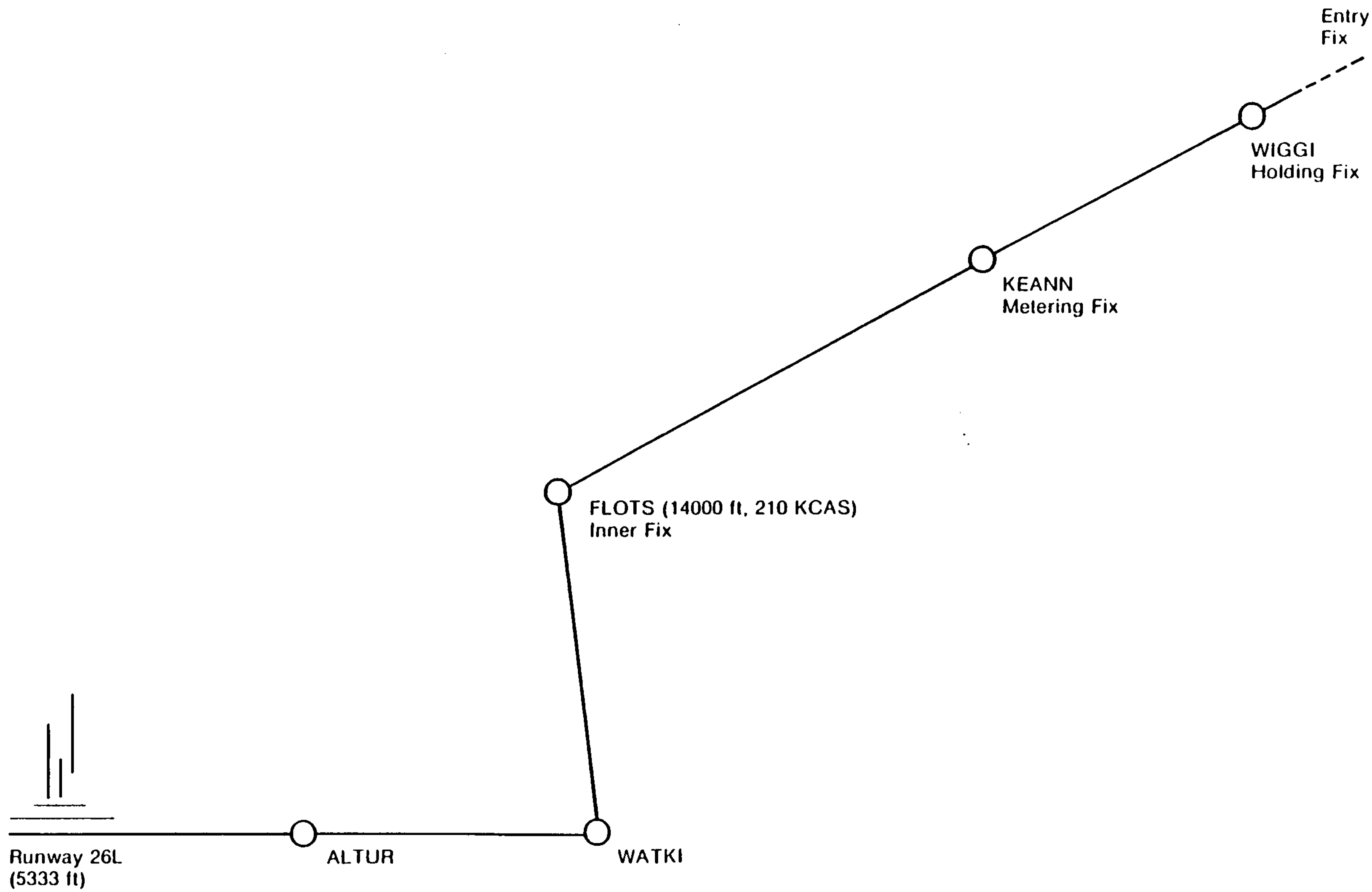


*Figure 12. Denver Stapleton KEANN 26 Approach*

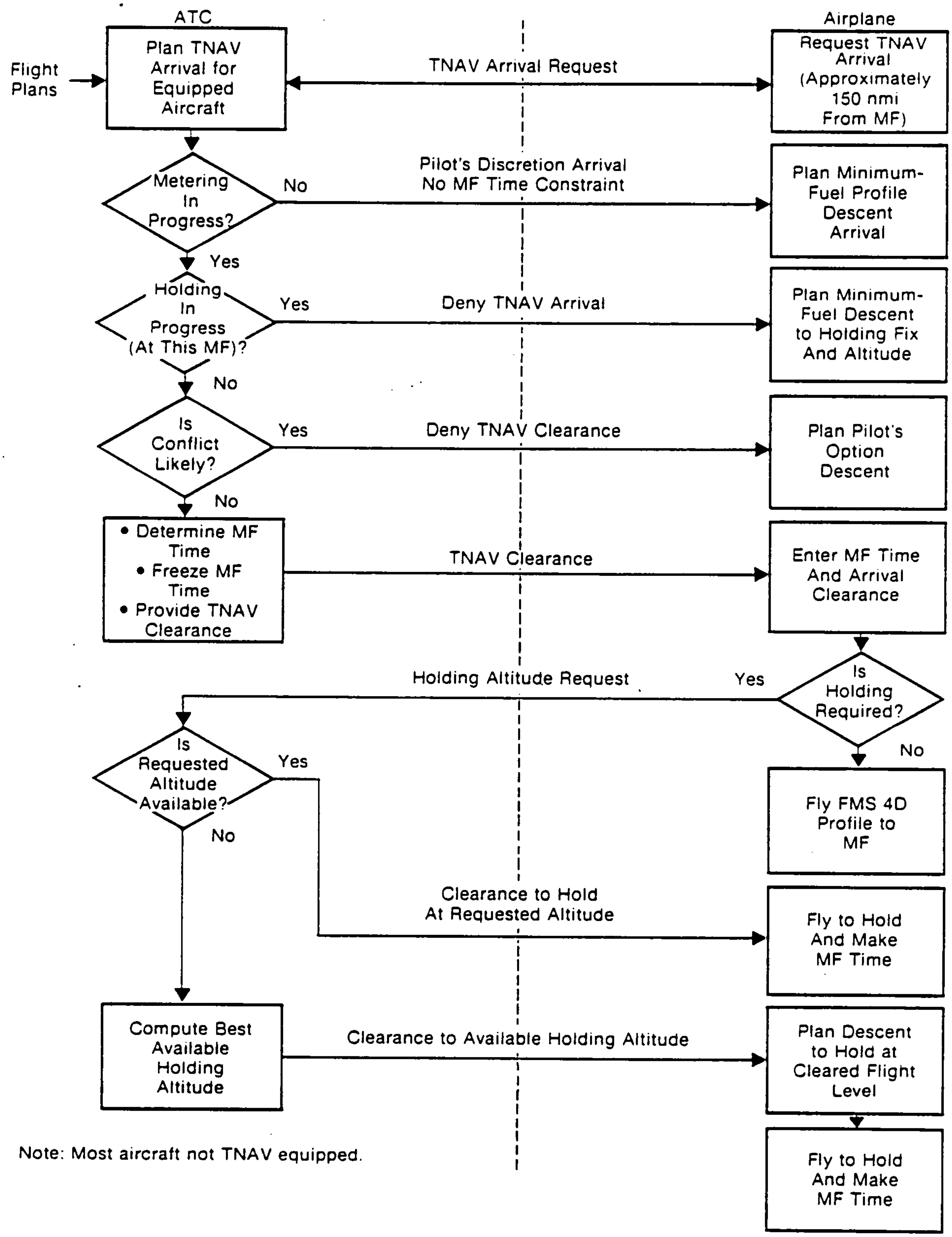


*Figure 13. TNAV Use in En Route Metering*

## IF METERING IS NOT IN PROGRESS

ATC: (C) "NASA 515, Center, metering is not in progress. Expect pilot's discretion descent."

Airplane: (C) "Center, NASA 515, understand. Expect pilot's discretion descent."

(A) Pilot will plan for minimum-fuel descent using the expected arrival clearance (e.g., pilot's discretion descent, runway in use, and published profile descent, or expected arrival route and altitude, based on experience). This will be a clean-idle descent at minimum fuel.

A description of events associated with the pilot's discretion descent is contained in Table 4 using the KEANN approach geometry at Denver and the NASA 515 performance characteristics.

## IF METERING IS IN PROGRESS WITH HOLDING (AT THIS FIX)

ATC: (C) "NASA 515, Center, be advised holding in progress. Expect further clearance."

Airplane: (C) "Center, NASA 515, understand holding in progress. Expect further clearance."

(A) Pilot will plan for minimum-fuel descent using the expected-arrival clearance.

## IF METERING IS IN PROGRESS WITHOUT HOLDING, BUT A TNAV CLEARANCE IS NOT DESIRABLE DUE TO POTENTIAL CONFLICT WITH OTHER TRAFFIC

ATC: (C) "NASA 515, Center, TNAV clearance is denied due to traffic. Expect further clearance."

Airplane: (C) "Center, NASA 515, understand TNAV arrival denied due to traffic. Expect further clearance."

(A) Pilot will plan for minimum-fuel descent using the expected-arrival clearance.

## IF METERING IS IN PROGRESS WITHOUT HOLDING, CONFLICT NOT LIKELY; A TNAV CLEARANCE WILL BE AUTHORIZED

ATC: (C) "NASA 515, Center, cleared for TNAV arrival, KEANN intersection at XXXX (time), runway 26L, low-profile descent, descend to FL 240 at pilot's discretion."

Airplane: (C) "Center, NASA 515, understand cleared for TNAV arrival, KEANN at XXXX (time), runway 26L low profile, descend to FL 240 at pilot's discretion."

(A) Pilot enters the assigned MFT into the FMS. The FMS will define the path and speed profile to meet the assigned MFT.

TNAV-descent events for the KEANN approach and the NASA TCV performance characteristics are contained in Tables 5 and 6.

*Table 4. Scenario for En Route Metering, Low-Delay Level, Pilot's Discretion Descent*

| Time (hr:min:sec) | Distance (nmi) | Altitude (ft) | Originator | Event |
|---|---|---|---|---|
| 11:56:00 | 225. | 35000 | NASA 515 | Requests TNAV clearance to Denver Stapleton |
| | | | Center | Transmits clearance to NASA 515:<br>(a) KEANN low profile descent to Runway 26L<br>(b) No time constraints |
| 11:58:00 | 210. | 35000 | NASA 515 | Clearance acknowledged<br>Clearance entered in flight management system<br>minimum-fuel descent approach path predicted |
| 12:00:00 | 195. | 35000 | NASA 515 | Descent engaged at entry fix<br>Speed change from 259 to 223 kcas |
| 12:15:29 | 94. | 35000 | NASA 515 | Top-of-descent for predicted path reached<br>Throttles to idle, descent initiated |
| 12:23:21 | 45. | 19050 | NASA 515 | Crosses meter fix and resumes descent |
| | | | Center | Transmits approach control frequency to NASA 515 |
| | | | NASA 515 | Contacts approach control for approach clearance |
| | | | Approach | Transmits clearance to NASA 515: ILS Runway 26L, FLOTS direct WATKI |
| 12:25:57 | 31. | 14000 | NASA 515 | Level-off to inner fix altitude<br>Decelerate from 250 to 210 kcas |
| 12:26:39 | 28. | 14000 | NASA 515 | Turn at FLOTS, fly direct to WATKI (to intercept final approach) and resume descent |
| 12:29:35 | 16. | 10000 | NASA 515 | Turn to final at WATKI, continue descent |
| 12:32:11 | 8. | 7200 | NASA 515 | Level off and decelerate from 210 to 180 kcas<br>Begin descent to runway from ALTUR |

| | |
|---|---|
| Descent time | 34 min 51 sec |
| Descent distance | 195 nmi |
| Descent fuel | 1396 lb |

*Table 5. Scenario for En Route Metering, Intermediate-Delay Level, TNAV Descent*

| Time (hr:min:sec) | Distance (nmi) | Altitude (ft) | Originator | Event |
|---|---|---|---|---|
| 11:56:00 | 227. | 35000 | NASA 515 | Requests TNAV clearance to Denver Stapleton |
| | | | Center | Transmits clearance to NASA 515:<br>(a) KEANN low profile descent to Runway 26L<br>(b) Meter fix time assigned 12:21 |
| 11:58:00 | 212. | 35000 | NASA 515 | Clearance acknowledged<br>Clearance entered in flight management system<br>Metered descent approach path predicted |
| 12:00:00 | 197. | 35000 | NASA 515 | Descent engaged at entry fix<br>Speed change from 259 to 258 kcas |
| 12:15:07 | 113. | 35000 | NASA 515 | Top-of-descent reached for predicted path<br>Throttles to idle, descent initiated |
| 12:19:29 | 55. | 19100 | NASA 515 | Level-off at meter fix altitude<br>Decelerate from 328 to 250 kcas |
| 12:20:45 | 47. | 19100 | NASA 515 | Crosses meter fix and resumes descent |
| | | | Center | Transmits approach control frequency to NASA 515 |
| | | | NASA 515 | Contacts approach control |
| | | | Approach | Advises NASA 515 to expect radar vectors at FLOTS due to traffic |
| 12:23:11 | 33. | 14000 | NASA 515 | Level-off to inner fix altitude<br>Decelerate from 250 to 210 kcas |
| 12:23:53 | 30. | 14000 | NASA 515 | Crosses FLOTS |
| | | | Approach | Transmits clearance to NASA 515: left turn to heading 140 to intercept localizer, cleared for ILS Runway 26L |
| | | | NASA 515 | Acknowledges clearance, turns to heading, resumes descent |
| 12:26:49 | 16. | 10000 | NASA 515 | Intercept localizer, continue descent |
| 12:29:24 | 8. | 7200 | NASA 515 | Level-off and decelerate from 210 to 180 kcas<br>Begin descent to runway from ALTUR |

Descent time 32 min 4 sec
Descent distance 197 nmi
Descent fuel 1583 lb

*Table 6. Scenario for En Route Metering, High-Delay Level, TNAV Descent With Holding*

| Time (hr:min:sec) | Distance (nmi) | Altitude (ft) | Originator | Event |
|---|---|---|---|---|
| 11:56:00 | 231. | 35000 | NASA 515 | Requests TNAV clearance to Denver Stapleton |
| | | | Center | Transmits clearance to NASA 515:<br>(a) KEANN low profile descent to Runway 26L<br>(b) Meter fix time assigned 12:40 |
| 11:58:00 | 216. | 35000 | NASA 515 | Clearance acknowledged<br>Clearance entered in flight management system<br>Metered descent approach path predicted with holding at 21000 feet at WIGGI<br>Holding altitude request transmitted to ATC |
| | | | Center | Clearance to hold at requested altitude |
| 12:00:00 | 201. | 35000 | NASA 515 | Descent engaged at entry fix<br>Speed change from 259 to 210 kcas |
| 12:13:14 | 122. | 35000 | NASA 515 | Top-of-descent reached for predicted path throttles to idle, descent initialized |
| 12:22:46 | 71. | 21000 | NASA 515 | Level-off to begin holding fix entry procedure |
| 12:24:51 | 61. | 21000 | NASA 515 | Initiate holding at WIGGI, advises Center |
| 12:37:56 | 61. | 21000 | NASA 515 | Depart holding at WIGGI, resume descent to meter fix, advises Center |
| 12:39:35 | 54. | 19100 | NASA 515 | Level-off at meter-fix altitude<br>Accelerate from 210 to 250 CAS |
| 12:40:09 | 51. | 19100 | NASA 515 | Crosses meter fix and resumes descent |
| | | | Center | Transmits Approach Control frequency to NASA 515 |
| | | | NASA 515 | Contacts Approach Control |
| | | | Approach | Advises NASA 515 to expect radar vectors at FLOTS due to traffic |
| 12:42:36 | 37. | 14000 | NASA 515 | Level-off to inner-fix altitude<br>Decelerate from 250 to 210 kcas |

*Table 6. Scenario for En Route Metering, High-Delay Level, TNAV Descent With Holding (Concluded)*

| Time (hr:min:sec) | Distance (nmi) | Altitude (ft) | Originator | Event |
|---|---|---|---|---|
| 12:43:17 | 34. | 14000 | NASA 515 | Crosses FLOTS, resumes descent |
| | | | Approach | Transmits clearance to NASA 515: left turn to heading 140 due to traffic |
| | | | NASA 515 | Acknowledges clearance, turns to heading |
| | | | Approach | Transmits clearance to NASA 515: further left turn to heading 124 due to traffic, intercept localizer, cleared for ILS approach Runway 26L |
| | | | NASA 515 | Acknowledges clearance, turns to heading |
| 12:46:40 | 20. | 10000 | NASA 515 | Intercepts localizer, continues descent |
| 12:50:34 | 8. | 7200 | NASA 515 | Level-off and decelerate from 210 to 180 kcas<br>Begin descent to runway from ALTUR |

| | |
|---|---|
| Descent time | 53 min 14 sec |
| Descent distance | 201 nmi |
| Descent fuel | 2411 lb |

# APPENDIX B

## AIRBORNE ALGORITHM MODULES

The following is a list of all the airborne LFM/PD modules and their functional descriptions:

| Module Name | Function |
|---|---|
| AALPHA | Calculates angle between inbound and outbound leg headings |
| ACCEL | Controls path computation over distance required for acceleration before the aimpoint |
| ADDTRP | Adds tropopause temperature and wind data to weather models |
| ADJA1 | Adjusts path computation for entry fix acceleration segment when required final speed is exceeded |
| ADJA2 | Adjusts path computation for entry fix acceleration segment when distance limit is exceeded |
| ADJD1 | Adjusts path computation for entry fix deceleration segment when required final speed is exceeded |
| ADJD2 | Adjusts path computation for entry fix deceleration segment when distance limit is exceeded |
| ADJTL1 | Adjusts altitude, time, fuel, and weight totals at the end of a descent calculation between holding altitudes |
| ADJTLA | Adjusts segment totals for altitude-constrained descents for time, fuel, and distance |
| ADJTLD | Adjusts segment totals for distance-constrained descents for time, fuel, and altitude |
| ALTC | Determines corrected net-thrust differential due to increased $F_n/\delta$ with altitude, given Mach number and altitude |
| ALTMTR | Supplies station altimeter setting |
| ALTSPD | Obtains altitude and speed constraints at each waypoint |
| ASGNA | Assigns the ATC-constrained maximum altitudes for all waypoints |
| ASGNV | Assigns the ATC airspeed constraints from aimpoint to meter fix |
| ATCAPP | Requests ATC approval for required deviations from geometry-defined minimum-altitude restrictions |

| Module Name | Function |
|---|---|
| ATMOS | Controls construction of wind and temperature models |
| AWCMP | Computes along-track wind magnitudes |
| BNKANG | Computes holding bank angle |
| BSACOS | Inserts change-of-speed fix after stack exit |
| CAS | Computes calibrated airspeed, given altitude, and Mach number |
| CDCL | Determines coefficient of drag, using stored drag polars, given Mach number, and coefficient of lift |
| CDSPLR | Determines incremental coefficient of drag available as a function of equivalent airspeed |
| CMACH | Converts a calibrated airspeed at altitude to a Mach number |
| CMSLPA | Converts Mean Sea Level (MSL) value to pressure altitude, using station-pressure correction |
| COMPCI | Completes altitude and airspeed information in the path array when the calculation reaches cruise altitude |
| CONMSL | Controls conversion of pressure altitudes to MSL altitudes |
| CONTPA | Controls conversion of MSL altitudes to pressure altitudes |
| CONVRT | Transforms wind forecast from rho-theta system to "to wind" zonal and meridional components |
| CORCPT | Obtains temperature at cruise altitude; computes error function; applies error function to forecast |
| CORCPW | Obtains wind at cruise altitude; computes error function; applies error function to forecast |
| CRFUEL | Computes fuel used in level cruise, given time |
| CSFIX | Inserts change-of-speed fixes before waypoints at which an acceleration or deceleration is required |
| DCTHA | Controls calculation of idle-descent fuel and time between holding altitudes |
| DCTTOT | Totals time, distance, and fuel for each altitude step in a descent calculation |

| Module Name | Function |
|---|---|
| DECEL | Controls path computation over distance required for deceleration before the aimpoint |
| DELAY | Controls construction of delay profile |
| DELTA | Determines pressure ratio at given altitude |
| DESCAS | Determines descent calibrated airspeed for a given critical altitude and Mach number |
| DETHLD | Displays detailed holding requirements |
| DFCTMX | Determines maximum spoiler factor used in previous segments requiring drag |
| DGPERI | Computes engine idle thrust, drag, and fuel flow for a altitude step in a descent calculation, given spoiler setting |
| DGPERT | Computes thrust, drag, and fuel flow for an altitude step in a descent calculation, given spoiler setting and airplane turbine rpm ($N_1$) thrust |
| DISDTI | Displays thrusted or spoiler descent requirements |
| DMACH | Determines equivalent cruise Mach that will transition at the critical altitude to the input calibrated airspeed |
| DRAG | Determines drag force, given the calibrated airspeed, altitude, gross weight, and flight path angle |
| DRIFT | Calculates drift from true course due to wind |
| DSAS | Establishes altitudes and speeds for an altitude step in a descent calculation |
| DSAS1 | Calculates altitudes and speeds for an altitude step in a descent calculation between holding altitudes |
| DSEG4A | Computes drag required to satisfy altitude and distance-constrained descent |
| DSEG4B | Computes final altitude, time, and fuel for given drag and speed schedule over fixed distance |
| DSEG4C | Computes final energy state and position fordistance-constrained descent segment requiring drag |

| Module Name | Function |
| --- | --- |
| DSEG4I | Computes final energy state and position for descent segment(s) requiring drag |
| EFACC | Controls path computations over distance required for acceleration after entry fix |
| EFDEC | Controls path computation over distance required for deceleration after the entry fix |
| EPR | Determines engine EPR given corrected $N_1$, Mach number, and altitude |
| ERRAS | Validates waypoint altitude and speed constraints |
| ERRRTE | Validates course and distance input data |
| ETIME | Computes total elapsed time for specified profile segment |
| EVGWT | Evaluates aimpoint gross weight estimate by comparing entry-fix calculated gross weight with input value |
| EXCAPP | Sets profile termination flag |
| FAMACH | Determines fastest Mach/CAS-descent within aeroperformance limits of the aircraft |
| FCSTKT | Determines forecast temperature at cruise altitude |
| FCSTKW | Determines forecast wind at cruise altitude |
| FUELFI | Determines idle-fuel flow, given Mach number and altitude |
| FUELFL | Determines fuel flow, given net thrust, Mach number, and altitude |
| GAMMA | Computes angle between inbound true heading and wind |
| GNDSPD | Computes groundspeed, given altitude, true airspeed, and course information |
| GTAS | Computes true airspeed from groundspeed, true course, and wind |
| GTFCST | Reads number of forecast altitudes and, for each altitude, the forecast wind direction and speed and forecast temperature |
| GTPRF | Accesses selected path from random access file |
| HALTMF | Computes fuel used at given holding altitude |

| Module Name | Function |
|---|---|
| HCCALC | Computes the critical altitude model (for transition from Mach to CAS schedule) as a function of true airspeed |
| HCRIT | Determines critical altitude from model computed in HCCALC |
| HDWND | Verifies that headwind components do not compromise timing at all holding altitudes |
| HEWPT | Inserts level segment prior to entering stack |
| HFIPA | Controls distance, speed, and altitude constraint calculations for the holding elements in the path array |
| HIGHPF | Selects method of computing the high profile required to meet metering conditions |
| HLDALT | Determines all holding altitudes between specified top and bottom altitudes |
| HLDINF | Obtains inputs to initiate holding path calculations |
| HLDNOA | Determines closest ATC holding altitude to single airplane, computed optimum holding altitude |
| HLDOA | Determines the closest holding altitude intersecting the calculated fuel-efficient profile at the holding fix |
| HLDPRF | Controls computation of the holding path |
| HLDSA | Obtains valid single-altitude assignment |
| HLDSPD | Obtains valid holding airspeed |
| HLDSTA | Obtains assigned top and bottom stack altitudes |
| HPD | Controls processing sequence in construction of profile from meter fix back to entry fix for a given speed schedule, using segment computation modules |
| HPRHLD | Coordinates construction of high-profile path with holding |
| IALTM | Determines weather model altitude closest to input altitude |
| ICESET | Obtains $N_1$ setting and icing altitude limits |
| ICING | Tests whether anti-icing procedures are in effect |

| Module Name | Function |
| --- | --- |
| ICPER | Computes engine idle, clean-configuration thrust, drag, and fuel flow for an altitude step in a descent calculation |
| IDHWPT | Obtains valid holding fix identifier |
| IDMFWP | Obtains meter fix |
| IDTFWP | Determines transition fix of the current approach route |
| INSERT | Creates a new waypoint position in the path array |
| INSHF | Inserts holding fix when no published waypoints lie between entry fix and meter fix |
| INSPOD | Inserts descent point distance, speed, and altitude into the path array |
| INSRTT | Creates new positions in the segment total time and fuel arrays |
| IROUND | Rounds input variable to nearest integer for display purposes |
| ITYPE | Determines the segment type, considering current airspeed and altitude and next waypoint's airspeed and altitude constraints |
| LINMDL | Constructs piecewise linear temperature or component wind model |
| LINREG | Solves the linear regression formula between two points |
| LOADAR | Accesses geometry and weight; determines altitude and speed constraints at waypoints for desired path; assigns selected geometry to path array; obtains initial conditions for the descent profile; controls path geometry revisions |
| MSEC | Converts time in decimal minutes to minutes and seconds |
| MSRCH | Determines descent Mach to meet time required at metering fix |
| NIREC | Compiles information for segments using thrusted or spoiler descents |
| NUMCIR | Computes initial number of circuits to absorb holding delay |
| NUMID | Numbers descent point and change-of-speed fix waypoints |
| NWPIDF | Determines numerical order of given waypoint |
| PAMSL | Converts pressure altitude to MSL, using station pressure correction |
| PATHST | Controls computation of path-stretching parameters |

| Module Name | Function |
|---|---|
| PDDIS | Displays tabular course, distance, time, altitude, speed, and fuel information for profile |
| PFCAS | Determines CAS for an altitude interval in a descent calculation, given a descent Mach |
| PSMTRF | Computes minimum circuit time, given wind, at optimum altitude |
| PSOFST | Computes path-offset distance and leg times |
| RDCALT | Obtains cruise altitude |
| RDMFT | Obtains MFT assignment |
| RDMTRS | Determines metering status |
| READIN | Obtains airport selection and profile descent path selection |
| REMOVE | Eliminates unnecessary change-of-speed segments |
| REPORT | Formats and writes out the computed profile descent |
| RETNII | Retrieves arrays for spoiler and thrusted descents from temporary storage |
| RETPTH | Retrieves path arrays for temporary storage |
| RHO | Determines atmospheric density at given altitude |
| RODALT | Computes minimum altitude corresponding to a 500-feet per minute descent rate over the specified distance |
| RODEND | Provides profile-calculation-termination messages due to insufficient descent rate |
| ROUTE | Inputs airway magnetic courses, variation and course distances |
| RVGEOM | Creates revised-path course, distance, and altitude constraints |
| RVPAPS | Revises path array to include offset waypoints required for path stretching |
| RVPATH | Controls revision of high-profile geometry to accommodate holding |
| RWYPF | Controls processing sequence in construction of profile from outer marker back to meter fix; uses segment computation modules |
| SEG1 | Computes time and fuel for level, unaccelerated flight over a given distance |

| Module Name | Function |
|---|---|
| SEG2 | Computes time, distance, and fuel to decelerate between two CAS at constant altitude |
| SEG3 | Computes time, distance, and fuel to accelerate between two CAS at constant altitude |
| SEG4 | Computes time and fuel for a descent between two waypoints; calls other descent segment types, as required |
| SEG4AC | Computes final energy state and position for an altitude-constrained descent segment |
| SEG4DC | Computes final energy state and position for distance-constrained descent segment |
| SEGCAL | Initiates the segment calculations; accesses the segment calculation routines according to segment type |
| SEGTOT | Computes total time and fuel for profile |
| SIGMA | Determines atmospheric-density ratio at given altitude, employing forecast temperature |
| SLMACH | Determines slowest Mach/CAS descent within aeroperformance limits of the aircraft |
| SPOILF | Determines percentage of available spoiler drag to converge on required distance and altitude |
| STGWT | Estimates aimpoint gross weight based on cruise, distance, and holding considerations |
| STINF | Coordinates computation of stack information |
| STPAT | Controls calculation of holding times and fuels |
| STRNII | Stores arrays for spoiler and thrusted descents in temporary storage |
| STRPTH | Stores path arrays in temporary storage |
| SUMARY | Controls summary of important profile information |
| SUMDLY | Displays summary of holding information |
| TAS | Computes true airspeed, given altitude, and Mach number |

| Module Name | Function |
|---|---|
| TEMPC | Evaluates temperature model at given altitude to determine forecast temperature |
| THETA | Computes temperature ratio at given altitude |
| THPER | Computes clean-configuration thrust, drag and fuel flow for an altitude step in a descent calculation, given thrust setting |
| THRSTF | Determines percentage of available thrust to converge on required distance and altitude |
| THRSTN | Determines corrected net thrust, given Mach number and engine exhaust pressure ratio |
| TIME | Adds elapsed time to clock time |
| TIMERQ | Translates assigned MFT into the required elapsed time for the high profile, using estimated-entry fix time |
| TLEG1 | Computes inbound leg time |
| TLEG2 | Computes outbound leg time |
| TMACH | Computes Mach number for a given altitude and true airspeed |
| TREV | Computes time to complete one circular revolution at constant bank angle |
| TREVA | Computes outbound-turn time |
| TREVB | Computes inbound-turn time |
| TRUALT | Converts pressure altitude into geopotential altitude, using temperature lapse rate and the hydrostatic equation |
| TSACOS | Provides for change-of-speed fix prior to entering stack |
| TSEG4A | Computes thrust required to satisfy altitude and distance-constrained descent |
| TSEG4B | Computes altitude, time, and fuel for a given thrust and speed schedule over fixed distance |
| TSTIDL | Determines net thrust at a Mach number and altitude, given idle engine setting |
| TSTMCL | Determines maximum climb thrust available at an altitude and Mach number |

| Module Name | Function |
|---|---|
| TSTMCR | Determines maximum cruise thrust available at an altitude and Mach number |
| TSTPAR | Determines net thrust, given Mach number, altitude, and corrected rotor speed |
| TSTPER | Computes thrust, drag, and fuel flow for an altitude step in a descent calculation, given a clean configuration and $N_1$ thrust |
| TTURNS | Controls calculation of inbound- and outbound-turn times |
| VALDTE | Validates input records after they have been displayed |
| VAREC | Records all altitude violations incurred during the descent-calculation process |
| VFAST | Determines high-speed CAS limit for a given altitude and weight |
| VLDAS | Displays and accepts corrections to waypoint altitude and speed constraints |
| VLDRTE | Displays and accepts corrections to course and distance data |
| VSLOW | Determines low-speed CAS limit for a given altitude and weight |
| WEIGHT | Obtains entry-fix gross weight acceptable within zero-fuel and maximum operating weights |
| WNDDIR | Evaluates wind model at given altitude to determine wind direction |
| WNDSPD | Evaluates wind model at given altitude to determine magnitude of wind velocity |

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16. Abstract

The design requirements for a 4D path definition algorithm are described. These requirements were developed for the NASA ATOPS as an extension of the Local Flow Management/Profile Descent algorithm. They specify the processing flow, functional and data architectures, and system input requirements, and recommend the addition of a broad path revision (reinitialization) functional capability. The document also summarizes algorithm design enhancements and the implementation status of the algorithm on an in-house PDP-11/70 computer. Finally, the requirements for the pilot-computer interfaces, the lateral path processor, and guidance and steering function are described.

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